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Experimental study of drying of hot chili

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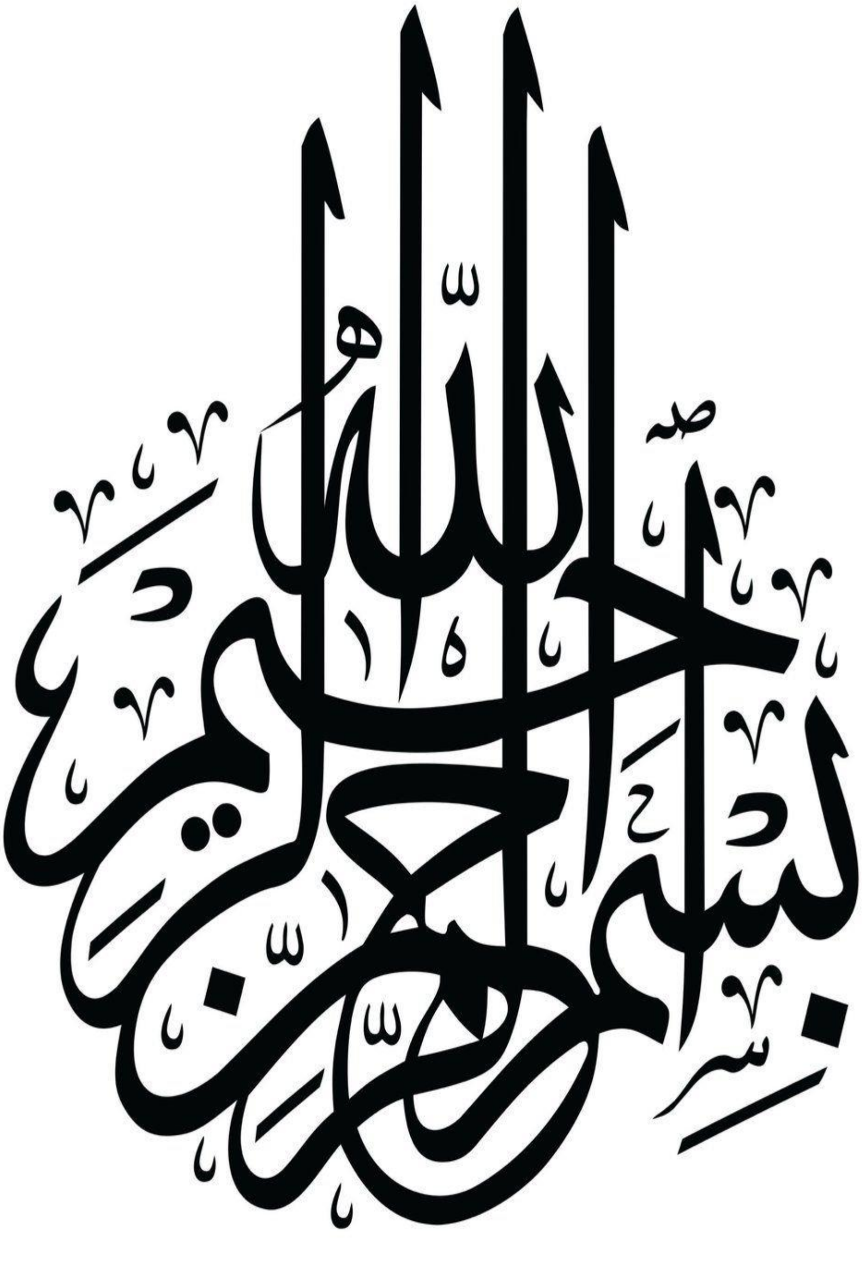
بسم الله الرحمن الرحيم

Dedications

I dedicate this work to my dear parents

To my mother, may Allah have mercy on her

To my dear sisters

To my dear brothers

To my supervisor Pr. Labed adnane

To all my colleagues and all my friends

To all those who helped me and encouraged me during

my studies and for all those who are dear for me

Thanking and appreciation

I thank Allah the Almighty who helped me to reach this advanced stage of the academic level.

I would like to thank in the first place, my supervisor Dr. Labed Adnane on his humility, his liberality, and his sacrifices to accomplish this work perfectly.

I would like to thank the members of jury, Dr. Moummi noureddine as a president and Dr. Chebeh Said as an examiner for their accept to be members of jury.

Finally, I would like to thank my family, my friends and anyone who supported me to finish this modest work.

«Nomenclature»

A:exposed surface area	m^2
Aw: water activity	
ERH: the equilibrium relative humidity	%
H:convection heat-transfer coefficient	$W/m^2.k$
Md:dry mass of product	kg
Mh:humide mass of product	kg
Moisture content (d.b):moisture content dry basis	$Kg_{wat}/kg.h$
Moisture content (w.b):moisture content wet basis	$Kg_{wat}/kg.h$
P:partial pressure of vapor at a temperature (T), at the surface of the wet sample	bar
P_0:partial pressure of saturated vapor in air in equilibrium with water at the surface	bar
Q=heat transfer rate	W
RH: relative humidity	%
Ta=ambient temperature	°C
X:absolute humidity of a solid	Kg_{wat}/Kg d.b
Xr: moisture content on a wet basis	Kg_{wat}/Kg w.b
$\dot{X}$:Drying rate	$Kg_{wat}/kg.h$ d.b

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General introduction

Drying is one of the oldest methods used to preserve food, and it has been used since oldest times and thousands of years ago (more than 4000 years ago) the Babylonians, Egyptians, Greeks and Romans in preserving some types of fruits, vegetables, meat, fish and milk … which lead to stop spoilage, save flavor and vitamins for product.

The method of preservation has been known by drying since oldest times, by utilizing solar energy, which is still used until now in drying some types of vegetables and fruits, but solar drying has been usually limited to dry climatic areas with bright sunshine, but with technological progress, many methods have been invented for drying using industrial methods. Which performs the desired purpose in a short period and with high efficiency, and the beginning was with industrial dryers, which are special ovens that depend on heat and hot air , but this method faces two main technical problems represented in the large consumption of energy, which makes its cost prohibitive, as well as the risk of changing in product (aroma, flavor...etc).

The main purpose of this work is to investigate the drying behaviour of thin layer of hot chilli by using drying oven, indirect solar dryer and sun drying.

Our manuscript consists of four chapters:

The first chapter provides a review of the importance of drying and also mentions generalities of drying, its methods and different types.

In the second chapter, an explanation of the concepts and equations of drying is presented.

The third chapter describes the experiment steps and shows all measuring instruments and the necessary materials to ensure the drying operation.

The last chapter explains and interprets the obtained experimental results, which were translated into curves.

Chapter
I

Generalities

I.1. INTRODUCTION

Dehydration is one of the oldest known methods of preserving food. Primitive people dehydrated or dried herbs, roots, fruits and meat by exposing them to the sun. They had learned that dehydrating food allowed them to survive the harsh, long winters when food was scarcer or even non-existent. The lightness and high nutritional value of dehydrated foods also allowed ancient peoples to travel greater distances on their hunting or exploration trips. Since the beginning of civilization, almost all the peoples of our planet have resorted to dehydrating or drying food. In fact, the oldest written documents on the subject mention that the Phoenicians and other fishing peoples of the Mediterranean used to dry their catches in the open air. Sun-drying tea leaves was widespread among the Chinese. Several other ancient cultures consumed various dehydrated foods. For example, when some ancient Egyptian tombs were excavated recently, scientists discovered a variety of dehydrated foods, including wheat grains. These foods were believed to support the spirit of the deceased on its afterlife journey. In an experiment, grains that were centuries old were subsequently rehydrated. Miraculously, they sprouted, proving that dehydration is truly a natural and viable way to preserve food for the long term. In the days of 15th and 16th century explorers, most sailors ate a variety of dried foods to maintain health during sea voyages.

Therefore, in this first chapter, we will see generalities about drying, such as drying methods and types...etc[1].

I.2. Drying

Drying is the oldest method of preserving food. Throughout history, the sun, the wind, and a smoky fire were used to remove water from fruits, meats, grains, and herbs. By definition, food dehydration is the process of removing water from food by circulating hot air through it, which prohibits the growth of enzymes and bacteria. Dried foods are tasty, nutritious, lightweight, easy-to- prepare, and easy-to-store and use. The energy inputs less than what is needed to freeze or can, and the storage space is minimal compared with that needed for canning jars and freeze containers[2].

I.2.1. Drying terminology

I.2.1.1. Humidity

This term indicates the liquid contained in the solid or liquid body, and which will have to eliminated due to drying[3].

I.2.1.2. Humidity rate

It is the liquid mass contained per unit mass of material to be dried, or it is the rate between the mass of the liquid contained in the humid body on the mass of the body[3].

I.2.1.3. States of dryness

An anhydrous body is a body with zero humidity. A dry or dried body more generally corresponds to the product as it is obtained at the outlet of the dryer. In the latter case, the humidity level is not necessarily zero[4].

I.2.2. Effect of parameters on drying

The most important parameters, which determine the quality of the dried product, are mentioned below:

I.2.2.1. Temperature

The drying temperature mainly determines the quality of the dried product. High drying temperature may impair the germination ability of seeds and can damage the product changing either the chemical combination or smoulder the product.

Lower drying temperature may lead to longer drying time which may lead microbial contamination[5].

I.2.2.2. Mass flow rate

Mass flow rate also plays an important role in drying process. Optimum mass flow rate is designed using the temperature requirement and the maximum air velocity, which can be maintained, inside the drying chamber[6].

I.2.2.3. Relative humidity of air

Relative humidity of air is defined as the ratio of the vapor pressure of air to its saturation vapor pressure. The equilibrium relative humidity (ERH) of a food product is defined as relative humidity of the air surrounding the food that is in equilibrium with its environment. When the equilibrium is obtained, the ERH (in percent) is equal to the water activity multiplied by 100, i.e. ERH (%) = $a_w \times 100$. When a food is exposed to a constant humidity, the product will gain or lose moisture until the ERH is reached. The moisture migration significantly affects the physical and chemical properties of the food, as previously described[7].

I.2.2.4. Moisture content of the drying product

The moisture content of the product to be dried is an important factor for determining the quality of the product and thereby the market value. Products with higher moisture content are found to have lesser drying time than those having very lesser moisture content[5].

I.2.3. Objectives of drying

- To reduce the food spoilage caused by larger production and limited usage.
- Prolonged usage of the product preventing them from spoiling due to microbial attacks.
- Drying will reduce the weight dramatically and makes transportation easy.
- High-quality dried product will have good market value and hence will bring high profit to the producers[8].

I.2.4. Factors influencing drying

Attributes of the food products that affect drying include :

- particle size
- particle shape
- composition, structure, and porosity
- moisture content
- specific heat capacity

Attributes of the drying equipment that affect food drying include

- type of dryer / dryer design
- air temperature
- retention time in dryer
- relative humidity of the drying air
- volumetric air flowrate
- seasonal and daily variations[9]

I.2.5. Effects of drying on products

- degradation of nutrients
- loss of structural integrity
- reduction of product functionality
- flavour and aroma changes
- colour changes[9]

I.2.6. Method of drying

I.2.6.1. Low-Temperature drying

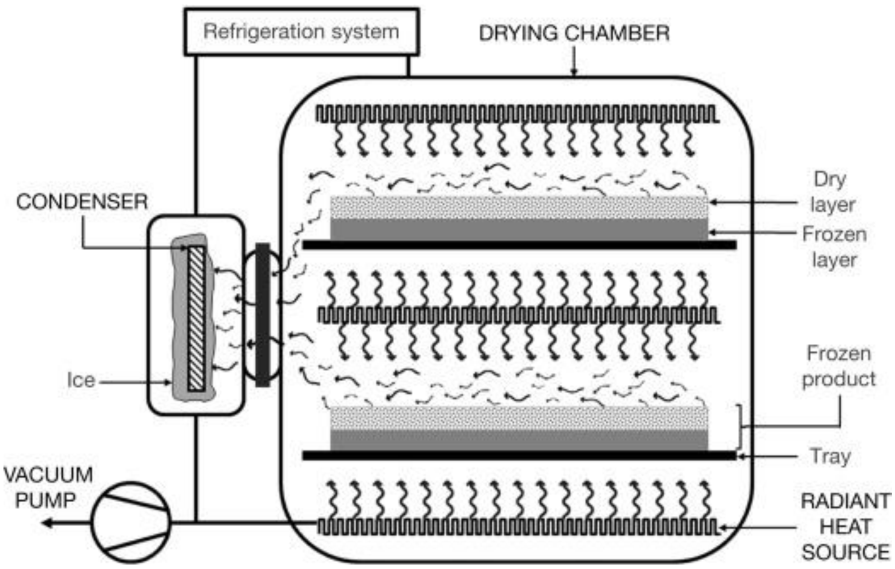
It is used for places where the average ambient temperature is around 10 °C. The temperature range used for this type of drying ranges from 15 to 50 °C. It uses natural or heated air with low temperature to dry the product in very longer time. Even though it is a relatively slower process and is dependent on favourable weather conditions, it has some advantages such as lesser spoilage, good quality product, less labour and capital investment[8].

I.2.6.2. High-Temperature drying

High-temperature drying uses temperature starting from 50 °C, and this is the most common method in developed countries. It is used for drying high moisture content products such as fruits and vegetables. A hot air recirculation system may be employed with a dehumidification unit to increase the effectiveness of the system with less wastage of energy[8].

I.2.6.3. Freeze-drying

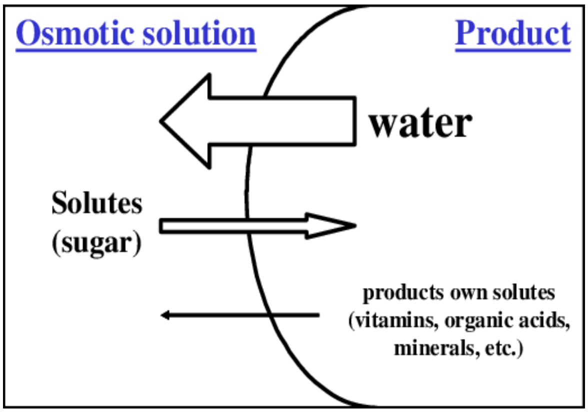
Freeze-drying or lyophilization is a drying process in which the solvent and/or the suspension medium is crystallized at low temperatures and thereafter sublimed from the solid state directly into the vapor phase[10].



Fig(I-1): Freeze dryer diagram.

I.2.6.4. Osmotic dehydration

The osmotic dehydration (OD) is a process that partially removes water from food material by means of food immersion in a hypertonic solution (i.e. sugar and salt). It is a counter-current mass transfer process, in which water is drained from the interior of the food to the hypertonic solution and the solute flows into the food. Generally, OD is a slow process depending on the permeability of cell membranes and cell architecture[11].



Fig(I-2): Principle of the osmotic dehydration.

I.3. Oven drying

Everyone who has an oven has a dehydrator. By combining the factors of heat, low humidity and air flow, an oven can be used as a dehydrator (Plate 4). An oven is ideal for occasional drying of fruit leathers, banana chips or for preserving excess produce like celery or mushrooms. Because the oven is needed for every day cooking, it may not be satisfactory for preserving abundant garden produce. Oven drying is slower than dehydrators because it does not have a built-in fan for the air movement. (However, some convection ovens do have a fan)[2].

Fig (I-3): Drying oven

I.3.1. Hot air oven parts and functions

1-External cabinet: The External cabinet is made of stainless sheets. It covers the inner chamber.

2-Glass wool insulation: The space between the inner chamber and external cabinet is filled with Glass wool. It provides insulation to the hot air oven.

3-Inner chamber: The inner chamber of the hot air oven is made of Stainless steel.

4-Tubular air heaters: They help to generate heat within the inner chamber. Two Tubular air heaters are located on both sides of the inner chamber.

5-Motor-driven blower: It helps in uniformly circulating the air within the chamber.

6-Temperature sensor: It measures the temperature within the hot air oven and displays it on the controller screen.

7-Tray slots: The inner wall of the chamber contains several try slots that hold the trays.

8-PID temperature controller: It maintains the accurate temperature during the entire cycle. It also controls the temperature and also displays the temperature values.

9-Load indicator: it indicates the hot air oven is overloaded.

10-Mains on/off switch: It helps to turn on/ turn off the hot air oven.

11-Safety thermostat: It is also known as an over-temperature protection device. It keeps your oven and specimen safe in case of controller malfunction[12,13].

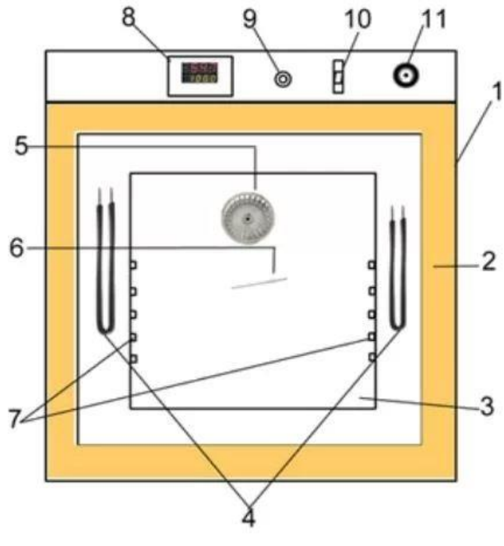


Fig (I-4): Drying oven diagram

I.3.2. Operating principles

Operating principles generally, drying ovens have an internal and an external chamber. The internal chamber is made of aluminium or stainless steel material with very good heat transference properties. It has a set of shelves made of stainless steel grids so that air circulates freely around objects requiring drying or dry heat sterilization. It is isolated from the external chamber by insulating material which maintains high temperature conditions internally and delays the transference of heat to the exterior. The external chamber is made of steel laminate, covered with a protective film of electrostatic paint. Heat is generated through sets of electrical resistors transferring this thermal energy to the chamber. These resistors are located in the lower part of the oven and heat is transferred and distributed by natural or forced convection (in oven with internal ventilators)[14].

I.3.3. Types of hot air oven

There are present different types of hot air oven such as :

Gravity convection

- Gravity Convection Air is distributed by spontaneous convection. As hot air flows up, a gentle flow holds temperatures moderately uniform inside a container and wholly uniform in any distinct position.

Forced convection ovens

- These ovens carry a fan that gives limited air circulation within the heating container.
- This method provides very fast heat up and restoration times, mixed with especially low-temperature differences inside the working chamber.
- Flexible vents and semi-forced exhaust deliver it a conventional sample-drying oven.

Mechanical convection

- Mechanical Convection is a gravitation convection oven served with a re-circulating fan in a working container.

Forced exhaust ovens

- In these ovens, air is pushed into the working container by a fan and scattered through an adaptable vent.
- This variety of oven is especially helpful in purposes where the heating process provides vapors or fumes that require to be immediately and continuously discharged from the working container.
- All of the forced air ovens consume at a higher percentage than a convection oven. Though, much larger forced exhaust velocities can be accomplished by adding an air channel and a flexible outlet.
- This adjustment takes an extra $100 and is totally achievable with forced convection ovens.

Side draught ovens

- Certain ovens produce airflow from one side to the other i.e. left to right.
- Speedy heat up and restoration time make this type of oven prototype for preheating plastic cloths(hospitals, etc.) or any profession where smooth sheets or plates are used[15].

I.3.4. Hot air oven application

It is used to dry glassware, sterilize N95 masks, general instruments, and packaging items in life science, microbiology laboratory.

Itis also used in chemical and pharmaceutical industries, food and beverage industries, textile industries.

It helps in the elimination of moisture from the material thus it is used in curing, drying, baking, and annealing.

It is also used for the Measurement of mixed liquor suspended solids (MLSS).

In certain laboratories and hospitals, it is used to store materials at a constant temperature[12,13,16,17].

I.3.5. Advantages and negatives of drying oven

Advantage

- Oven drying is distinguished from natural drying by the quality, cleanliness and high nutritional value of the product.
- It can also be done at any time, in any country, from a factory that needs a small area and a huge production.
- The first basis in drying oven is the use of an appropriate temperature to give a dried substance with an acceptable taste and attractive color and reduce the percentage of loss of nutrients and vitamins.
- Not affected by weather.
- The operating process is simple while the equipment is generally simple and inexpensive.

Negative

- This method requires extended heating periods and cooling phases, meaning it usually takes hours to produce results. Procedures are laborious and tedious, involving many manual steps.
- The need for electrical energy.
- The high electricity cost in some countries may make drying by drying oven unfeasible.

- The operation could easily lead to considerable shrinkage of the product (mainly at the beginning of the operation) and a noticeable loss of nutritional quality (at the end of the operation due to the generally long drying time)[16].

I.4. Solar collectors

Solar energy collector is a special type of heat exchanger that transforms solar radiation energy into internal energy of the transport medium. Basically, there are two types of flat-plate solar heating collectors; water heating collectors and air heating collectors. The pace of development of air heating collector is slow compared to water heating collector mainly due to lower thermal efficiency. Solar air collectors are widely used for low to moderate temperature applications like space heating, crop drying, timber seasoning and other industrial applications. Conventional solar air collectors have poor thermal efficiency principally due to high heat losses and low convective heat transfer coefficient between the absorber plate and flowing air stream. Attempts have been made to improve the thermal performance of conventional solar air collectors by employing various design and flow arrangement[18].

I.4.1. Components of solar air collectors

Glazing: One or more sheets of glass or other diathermanous (radiation-transmitting) material.

Tubes, fins, or passages: To conduct or direct the heat transfer fluid from the inlet to the outlet.

Absorber plates: Flat, corrugated, or grooved plates, to which the tubes, fins, or passages are attached. The plate may be integral with the tubes.

Headers or manifolds: To admit and discharge the fluid.

Insulation: To minimise the heat loss from the back and sides of the collector.

Container or casing: To surround the aforementioned components and keep them free from dust, moisture, etc[19].

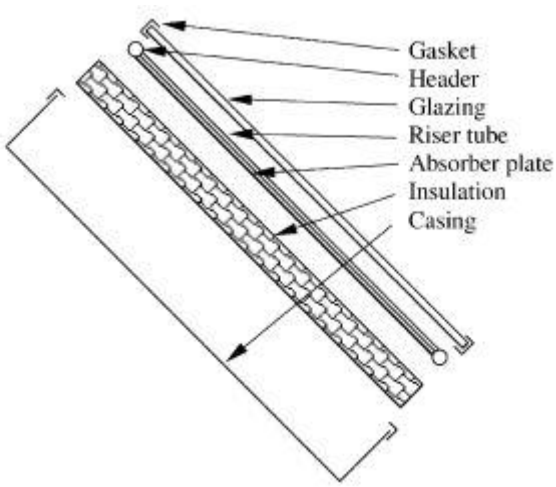


Fig (I-5): Exploded view of a flat-plate collector.

I.4.2. Principle of a plane solar collector

The solar collector plays a role in converting solar energy into thermal energy at low or medium temperatures. The technology depends on the type of surface, whether it is absorbent or not.

During the absorption process there is a part that is reflected in the air and this depends on the type of surface[20].

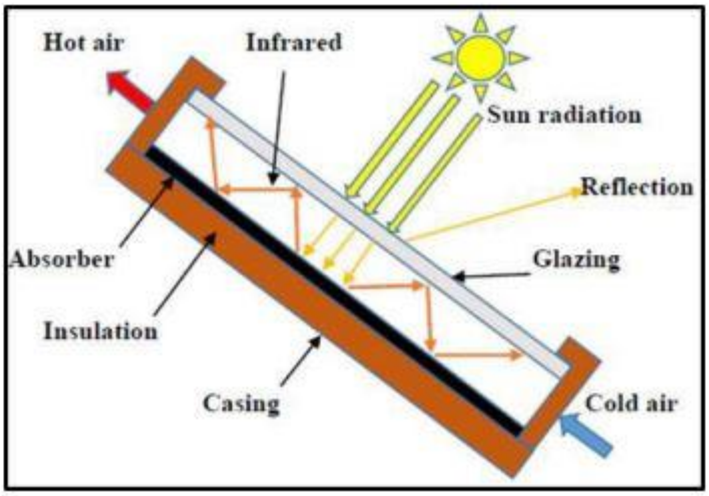


Fig (I-6): Principle of solar heat collector.

I.5. Type of Solar drying

I.5.1. Sun drying

In many countries with high amounts of sunlight and relatively low levels of humidity, raw materials are traditionally dried directly in the air. The natural raw materials are laid out on an open surface for several days, during which time they are turned over multiple times in the sun. This natural process removes water from the natural raw materials, sharply reducing their water content. The amount of moisture that is still retained after this process varies according to product type and customer request. Sun drying is a simple and cost-effective natural process that is used especially frequently for Mediterranean herbs, spices and dried fruits[21].

Fig (I-7): Sun drying of apricots

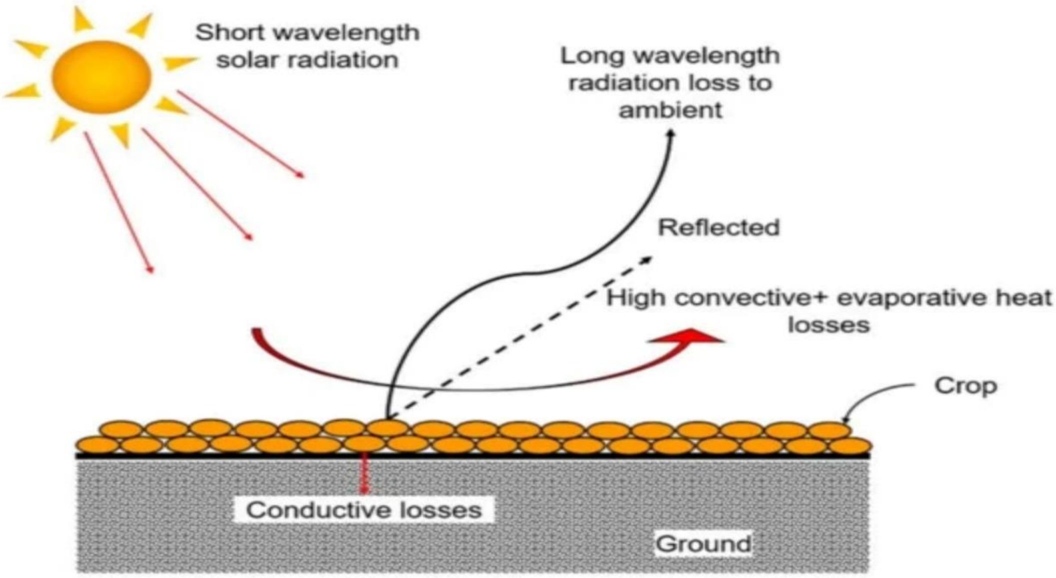


Fig (I-8): Principe of sun drying

I.5.1.1. Advantages and negatives of sun drying

Advantage

- Requires no materials or skilled labor
- Simple and inexpensive process
- Free and non-polluting solar energy source
- No energy expenditure

Negatives :

- A long drying time (possibility of rot)
- Alteration of product quality by solar radiation.
- the efficiency of the process is low given the numerous hazards (weather, constituents of the product sensitive to ultraviolet radiation, insects, rodents,

I.5.2. Direct solar drying

Direct solar dryers can be classified as box/cabinet-type, tent-type, and greenhouse-type solar dryers. In direct solar dryers, the products are placed in the heating unit that is covered with transparent cover. Thus, the same unit serves as an air heater and drying unit. Box-type solar dryer is an example of direct solar dryers . It consists of a quadrilateral-shaped box, trays of product, and transparent cover at the top. Solar radiation is transmitted through the transparent cover and absorbed on blackened interior surface. Due to accumulation of energy, the temperature inside dryer increases. As the temperature inside the dryer rises, the air enters into the dryer through holes in the front panel and passes out of the dryer through the hole in the rear panel due to the buoyancy-induced airflow. As a result, there is a continuous flow of air over the drying material. This type of solar dryer is very well suited to dry the small quantities (10–15 kg) of fruits and vegetables on domestic household scale[22].

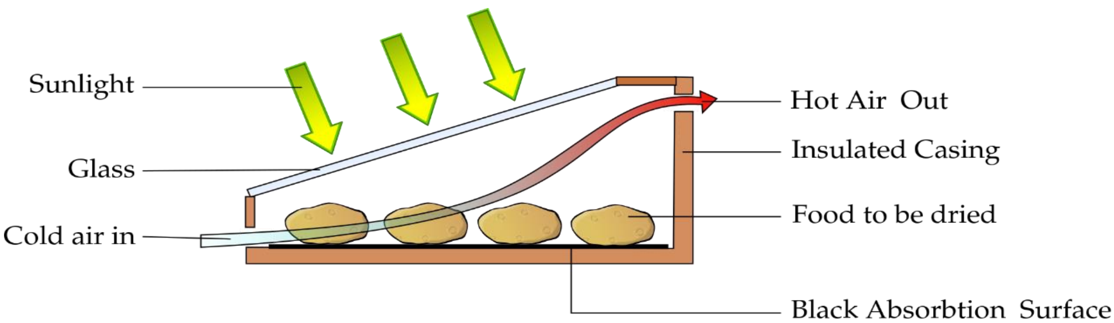


Fig (I-9) : Principe direct solar drying

I.5.2.1. Advantages and negatives of direct solar drying

Advantages

- Much better protection against dust, insects, animals and rain compared to traditional drying.
- Grandes possibilities de conception.

Negatives

- Quality degradation by direct exposure to sunlight, destruction of vitamin A and B, discoloration.
- Fragility of polyethylene materials that must be changed regularly.
- Poor air circulation which limits the speed of drying and increases the risk of rot[23].

I.5.3. Indirect solar drying

It is the oldest type of solar dryer, and it consists of a separate solar collector with a transparent cover on the top and a drying unit with an opaque cover on the top. These are connected in series (Fig I-10). In such a dryer, the crop is contained within the drying cabinet in a relatively thin bed, which completely spans the cabinet. Air, which is heated in a simple flat-plate-type solar collector, then flows as a result of the buoyancy forces resulting from the temperature differences up through the crop bed thereby producing the drying air. The drying rates achieved to date with these dryers have not, generally, been very satisfactory[22].

Fig (I-10): Indirect solar drying

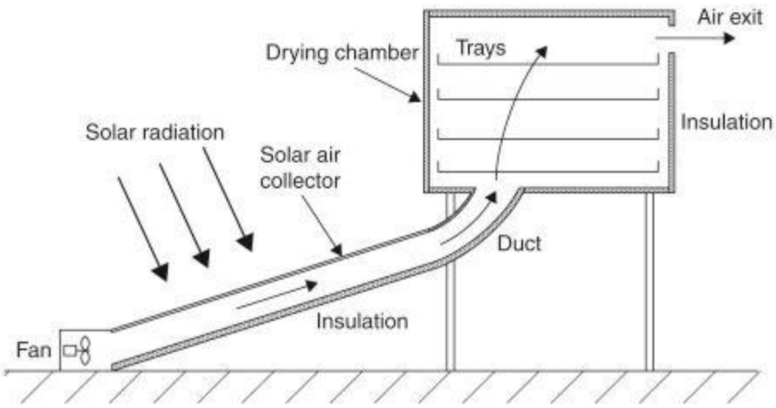


Fig (I-11): Principe indirect solar drying

I.5.3.1. Advantages and negatives of indirect solar drying

Advantages

- The product is not exposed to direct sunlight.
- It retains its colour and nutritional value better.
- Possibility to build this type of dryers locally, with a reduced cost.
- It does not require electricity or fuel to operate.

Negatives

- Drying rate depends on climate.
- Fragility of materials that must be changed regularly[23].

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Chapter
II

Theorical study

II.1. Introduction

After having presented the different drying technologies and before passing to the drying process, we must be familiar with many concepts and equations because this will help us to carry out a successful drying process, and this is what we will present in this chapter.

II.2. Drying Terminology

II.2.1. Humidity

This term indicates the liquid contained in the solid or liquid body, and which will have to eliminated due to drying[1].

II.2.2. Humidity rate

It is the liquid mass contained per unit mass of material to be dried, or it is the rate between the mass of the liquid contained in the humid body on the mass of the body[1].

II.2.3. Absolute humidity of a solid

Also known as moisture content on a dry basis, it is simply the mass of the liquid contained in the product compared to its dry mass[2].

$$\mathbf{X} = \frac{\mathbf{Mh - Md}}{\mathbf{Md}}$$

Where:

X : Absolute humidity of a solid [kg/kg (M_d)]

M_h : Humid mass of product [kg].

M_d: Dry mass of product [kg].

II.2.4. Relative humidity

Also known as moisture content on a humid basis (wet basis), it is the mass of the liquid contained in the product compared to its humid mass[3].

$$X_r = \frac{\mathbf{Mh - Md}}{\mathbf{Mh}}$$

Where:

X_r: Moisture content on a humid basis [kg_{wat}/kg] (w.b).

M_h : Humid mass of product [kg].

M_d : Dry mass of product [kg].

II.3. Drying rate

Drying rate is the rate at which internal moisture evaporates to the surroundings. It is dependent on the rate at which heat is applied to the product and also the rate at which moist air is removed from the surroundings. Definition by :

$$\dot{X} = -\frac{dX}{dt} = -k(X_f - X_0)$$

where K is the time constant (s-1)[4].

II.4. Stage of drying

In most references in the literature, there are generally three distinct phases involved in the drying process. At first, the product may go through a warm- up period . It will then need to be heated to a temperature at which evaporation of the moisture from the product can begin. The duration of this period is highly variable and depends on a number of factors including the moisture content of the product and the product's specific heat capacity. Conditions within the dryer also play a key role in determining the warm up period. The second stage is the constant rate period. During this period, drying proceeds by loss of water vapour from the saturated surface of the material into the surrounding air . moisture from within the material travels to the surface to maintain the saturated state there. This period of drying is controlled by the rate of heat transfer to the surface of the material being dried. the temperature of the material being dried remains relatively constant throughout this period. A point will be reached during the drying process when the surface is no longer saturated. There is no longer a "pool" or layer of moisture at the surface of the material. The drying mechanism now enters the falling rate period. There can actually be two zones of drying within this period.

The falling rate period begins after the constant rate period ends and moisture continues to diffuse from the inside of the material to its surface. However, the rate of diffusion is not sufficient to maintain saturated conditions at the surface. As moisture continues to be removed during this unsaturated surface drying, the rate of moisture removal slows or "falls". Eventually, the rate of evaporation exceeds the rate of diffusion . The drying front then moves inwards towards the center of the material; this then becomes the internal moisture movement control zone. While we are restricting our focus on drying to water removal, we should be mindful of the fact that other liquids such as organic solvents may require removal by drying[5].

II.5. Heat transfer

Heat transfer and mass transfer are critical aspects in drying processes. Heat is transferred to the product to evaporate liquid, and mass is transferred as a vapor into the surrounding gas. The drying rate is determined by the set of factors that affect heat and mass transfer. Solids drying is generally understood to follow two distinct drying zones, known as the constant-rate period and the falling-rate period. The two zones are demarcated by a break point called the critical moisture content[6].

II.5.1. Conduction

Conduction (contact drying) Contact drying involves an indirect method for removing liquid from a solid material by applying heat. In contact drying, the heat-transfer medium is separated from the material to be dried by a metal wall.

Conduction is used to dry liquids and pastes …. Etc[7].

II.5.2. Convective

hot and dry gas (usually air) is used both to supply the heat necessary for evaporation and to remove the water vapor from the surface of the food, definition by:

$$Q=h.A.\Delta T$$

Where :

Q = heat transfer rate

H = convection heat-transfer coefficient

A = exposed surface area

Δt = temperature difference

Uses in : Drying aromatic plants, fruits, grains ...etc[8].

II.5.3. Radiation

The energy used in drying the material is caused by electromagnetic waves, and the radiation used is either infrared or waves of the micro class[9].

II.6. Water activity

The water activity (a_w) of a food is the ratio between the vapor pressure of the food itself, when in a completely undisturbed balance with the surrounding air media, and the vapor pressure of distilled water under identical conditions. A water activity of 0.80 means the vapor pressure is 80 percent of that of pure water. The water activity increases with temperature. The moisture condition of a product can be measured as the equilibrium relative humidity (ERH) expressed in percentage or as the water activity expressed as a decimal definition by : $A_w=\frac{P}{P0}$

Where :

P: partial pressure of vapor at a temperature (T), at the surface of the wet sample

P_0: partial pressure of saturated vapor in air in equilibrium with water at the surface of the sample under consideration at (t)

Most foods have a water activity above 0.95 and that will provide sufficient moisture to support the growth of bacteria, yeasts, and mold. The amount of available moisture can be reduced to a point which will inhibit the growth of the organisms. If the water activity of food is controlled to 0.85 or less in the finished product[10].

II.7. Quality of dried products

II.7.1. Physical changes and mechanisms of dried products

Different phenomena linked to water loss and temperature variation with time are observed in the course of drying:

- glass transition, crystallization .
- melting of fat .
- evaporation of volatile components
- The migration of solutes to the surface leading to an accumulation of sugars and other solutes at the surface of the product. this accumulation is harmful to the quality of the product which must generally be consumed rehydrated.
- Changing the shape: in general, the departure of water from the product causes the product to collapse on itself. However, in certain situations, a very rapid departure of water and the existence of a solid matrix makes it possible to obtain a product of the same volume but with a porous structure[3,11].

II.7.2. Biochemical reactions induced by drying

As a general rule, high drying temperatures tend to spoil the quality of food products. But it would be more precise to say that these quality changes are time- and temperature-related. Both parameters enhance the reaction rates, which also strongly depend on the water activity aw of the products.

Many biochemical reactions can be induced by temperature increase in foods: Maillard reactions, vitamin degradation, fat oxidation, denaturation of thermally unstable proteins (resulting in variation of solubility or of the germinating power of grains, for example), enzyme reactions (which can either be promoted or inhibited), and so on. Some of these biochemical reactions generate components suitable, for example, for their sensory properties (flavor development); others may be more or less undesirable for nutritional or potential toxicity reasons (vitamin losses, changes in color, taste or aroma, formation of toxic compounds). All the reactions are linked to the simultaneous evolution of product composition, temperature and water content (or chemical potential, or water activity), these factors varying differently from one point to another, from the center to the surface of the products [11].

II.7.3. Loss of product color

Color is one of the most relevant attributes with respect to the quality of dried foods, because it is part of their visual appearance and it is, therefore, most of the time one of the first criteria taken into account by consumers when choosing a new product. Color can change during drying due to chemical and biochemical reactions. The rates of such reactions depend strongly on the drying methods and the processing parameters. The color of fruit, vegetables, aromatic plants and spices is due to the presence of pigments (carotenoids, chlorophylls, anthocyans, betalains) which are susceptible to degradation by enzymatic or non-enzymatic reactions, induced by drying and continuing during storage (Marty-Audouin et al., 1992)[11,12].

II.7.4. Loss of aroma

Drying is a separation process based on volatility. Therefore, the water contained in the product to be dried will not be eliminated on its own, but with any other volatile product also existing in the product, in most cases these are the aromas contained in organic products intended for food, for example for a product such as mint, Bouverat-Bernier et al , have shown that during drying at a constant temperature less than or equal to 55°C, the losses in essences (aromas) are of the order by 5%[3].

II.8. Conclusion

In this chapter, we looked at the theoretical side of drying, where we got acquainted with many important concepts that must be known before values in the drying process (such as heat transfer, water activity…. Etc.),because it will contribute to obtaining a successful drying process.

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Chapter III

Experimental study

III.1. Introduction

Drying is one of the processes that has found application in Algeria, due to the important amounts of solar radiation that can be exploited in this country, and the main purpose of this process is to preserve agricultural products for use at any time.

This chapter aims to introduce the place and the equipment used in this experiment. and Some samples were presented after the drying process.

III.2. Experiments location and zone climate

III.2.1. Experiments location

The experiments were carried out near the technological hall of mechanical engineering(solar drying) and the new technological hall (oven drying) from university of Biskra, which is located at latitude 34°48’ and longitude 5°44’, in the south-east of Algeria with 120 m of altitude in relation to the level of the sea, the city lies about 400 km from Algiers.

Fig (III-1) : Satellite picture of the experience area.

III.2.2. Experiments zone climate

Biskra takes place in the arid region, it is characterized by a very hot and dry summer; the average temperature is 43.5 °C with 12% of relative humidity in the average, and a very cold winter; average minimum temperature of 4 °C with an average maximum relative humidity of 89%.

III.3. Experimental study

In our study, we focused on drying green chili using a drying oven and a solar dryer that contains a drying room, in additional to the natural drying during the period between February and April 2022.

III.3.1. Experimental Procedure

In our experiments, we dried green chili using drying ovens and a solar dryer that has a drying chamber,We also used the natural drying method. Where we took samples of green chili weighing 100 grams and dried them, And to perform these experiments, we needed some tools and equipment, which were:

We used for the drying process of chili

Fig (III-2): Drying oven

We used for the drying process of chili

Fig (III-3): Solar collector with fan

We used the balance machine to measure the mass of the sample over time.

Fig (III-4): Balance machine

We used to measure the temperature and humidity inside the drying oven and drying room of the solar dryer.

Fig (III-5): A thermometer-control (Model TPM-10).

pyranometer (Volt raft model PL-110SM) Measure the intensity of solar radiation per unit W/m² as shown in Figure (III-6)

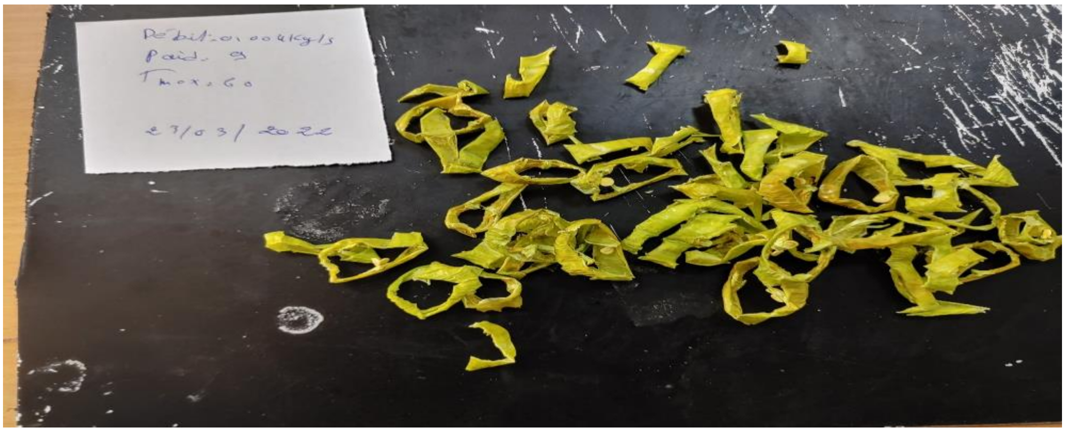
Fig (III-6): Pyranometer

We used it to measure the intensity, frequency and capacity of electric current

Fig (III-7): Power meter

III.4. Dried samples

In the figures bellow, we present the results of the drying process photos; it is a dried sample of sliced hot chilli (Figs. III.8-14).



Fig(III-8): Green chili after drying in oven drying in 60 °c with flow=0.004kg/s

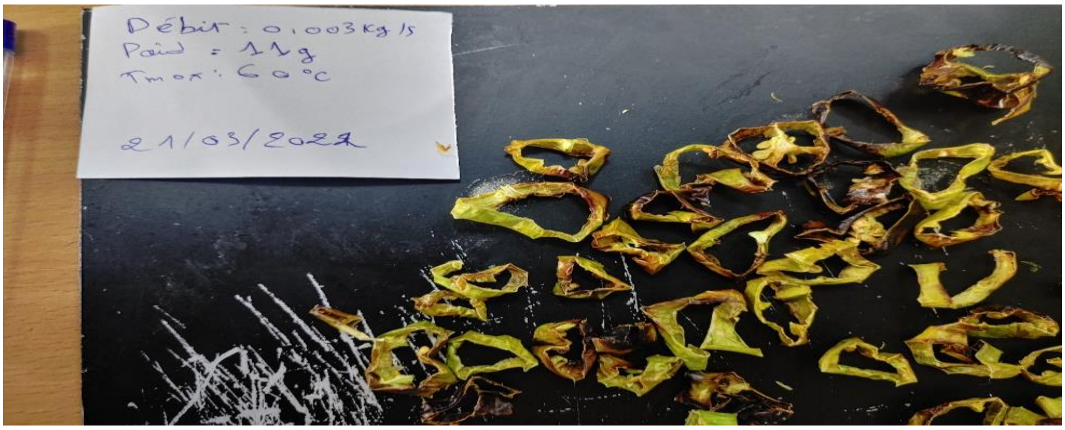


Fig (III-9): Green chili after drying in oven drying in 60 °c with flow=0.003kg/s

Fig (III-10): Green chili after drying in oven drying in 60 °c with flow=0.001kg/s

Fig (III-11): Green chili after drying in oven drying in 50 °c with flow=0.004kg/s

Fig (III-12): Green chili after drying in oven drying in 50 °c with flow=0.003kg/s

Fig (III-13): Green chili after drying in oven drying in 40 °c with flow=0.003kg/s

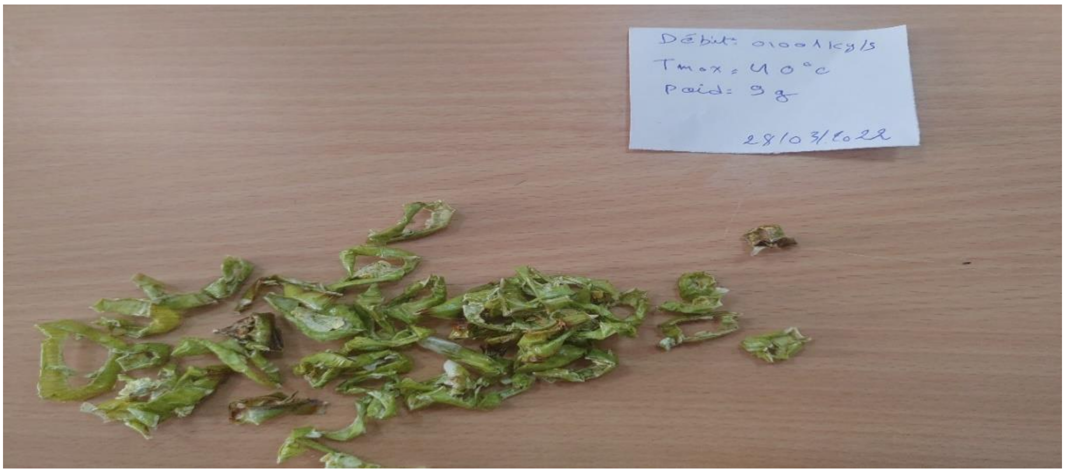


Fig (III-14): Green chili after drying in oven drying in 40 °c with flow=0.001kg/s

Chapter IV

Results and discussion

IV.1. Introduction

In this part, we will present the results of our experimental study carried out at the University of Biskra during the months of March and April 2022. We have focused on the combined effect of different parameters influencing the drying kinetics such as the speed of the drying air (air flow rate) and drying temperature. Thus we used two drying devices; electric oven and a solar dryer.

IV.2. Variation of moisture content (dry basis)

To study the influence of the air flow rate on the moisture content, we have used oven drying with three different temperature 40,50 and 60°c , and For each temperature we tried three different air flow rate 0.001,0.003 and 0.004kg/s .

Fig IV-2a illustrate how the moisture content variation is affected during the drying time in Temperature 60 °c. Drying was started with initial moisture content of (13.28 kg_{wat}/kg(d.b)) and continued to decrease until a final moisture content of the samples ranged from 0.43 to 0.86 kg_{wat}/kg (d.b) attained after 4 h 30 min.

Time taken to reach particular moisture content from the initial moisture content It changes according to the flow value, Where it reach in air flow 0.003 and 0.004kg/s to (0.42 Kg_{wat}/kg(d.b)) Within a period of 4 h 30 min ,while in the air flow 0.001kg/s it reached the same value but in longer time then the other air flows (5h)

Fig IV-2b show how the moisture content variation is affected during the drying time for T=50°c,As the moisture content decreases its value from 13.28 to 0.43 Kg_{wat}/kg(d.b) as lowest value .

The drying time with the first air flow rate (0.001 kg/s) is longer 8 h 00 min but is equal to 6 h 30 min and 5 h 30 min with the second, and the third flow rate (0.003 and 0.004 kg/s),

Fig IV-2c shows the effect of air flow on drying time in temperature equal 40°c,fast drying time was in air flow equal 0.001 kg/s on 9h 00min and in the other air flow 0.003kg/s ,0.004kg/s drying time was 11h 00min , 10h 00min.

Figures IV-2d and IV-2e present how the moisture content variation is affected during the drying time in solar drying (Forced convection and natural convection) and sun drying.

For solar Drying, was started with initial moisture content of (13.28kg_{wat}/kg (d.b)) in both of them (Forced convection and natural convection)then started decreasing ,we noticed in first four hours that natural convection value better then force convection, after that, the situation changed as forced convection value become better then natural convection and that continue till end drying process.

For natural drying, the process was started with initial moisture content of (13.28kg$_{wat}$/kg (d.b))then started decreasing till reached (1.71 kg$_{wat}$/kg (d.b)).

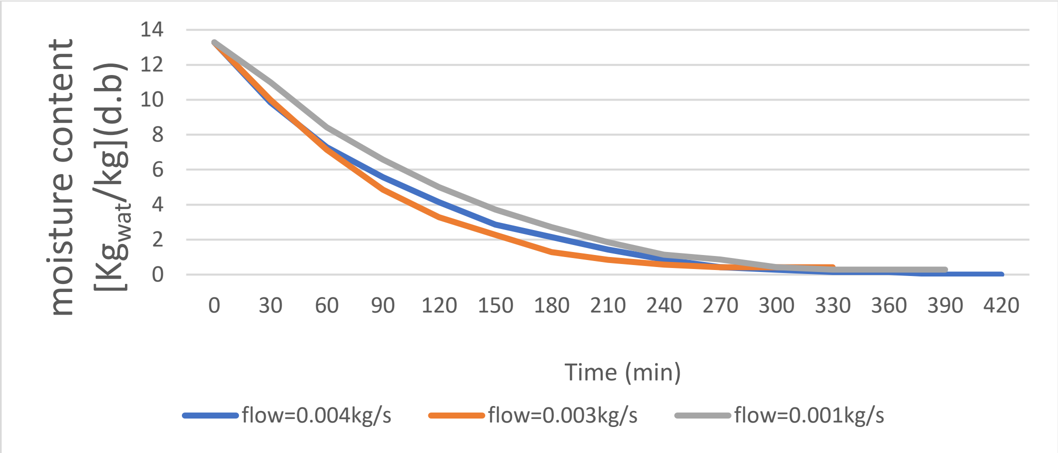


Fig (IV-2a): Variation of moisture content(d.b) with 3 different air flow(T=60°c)

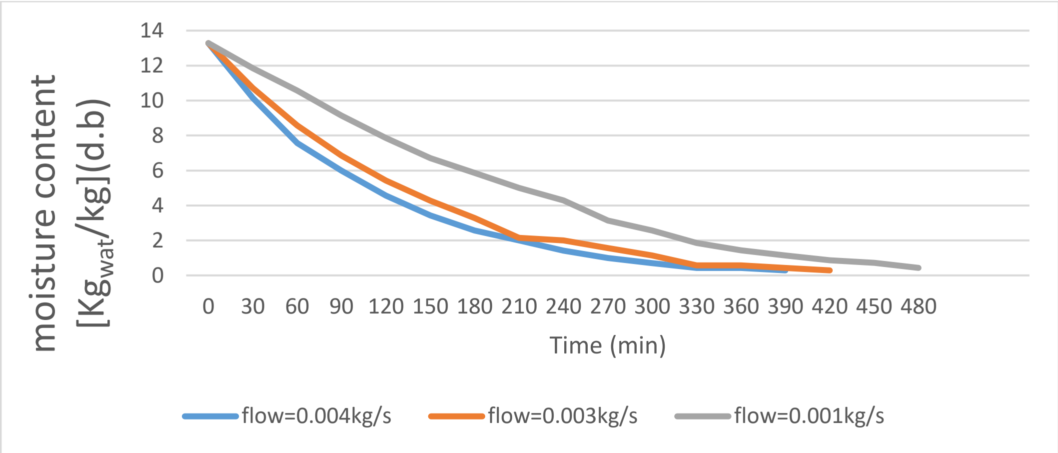


Fig (IV-2b): Variation of the moisture content (d.b) with 3 different flow (T=50°c)

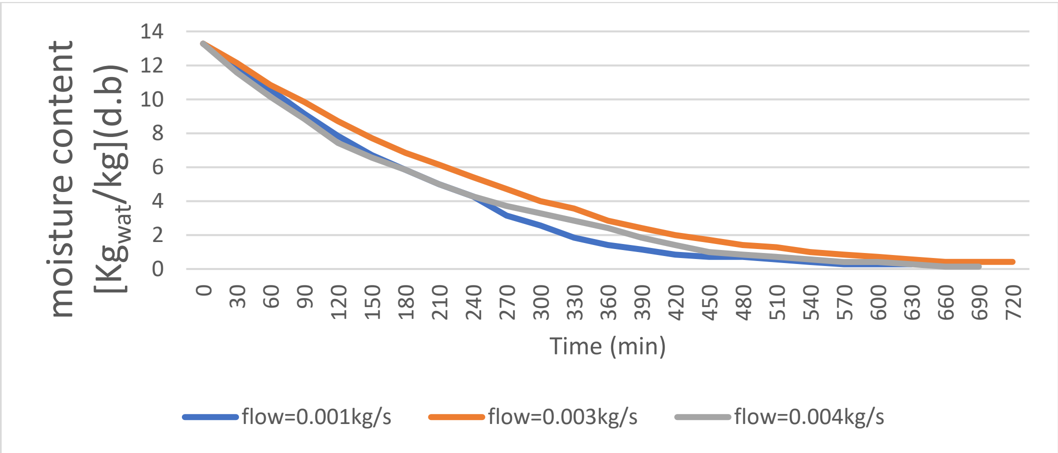


Fig (IV-2c): Variation moisture content (d.b) with 3 different flow (T=40°c)

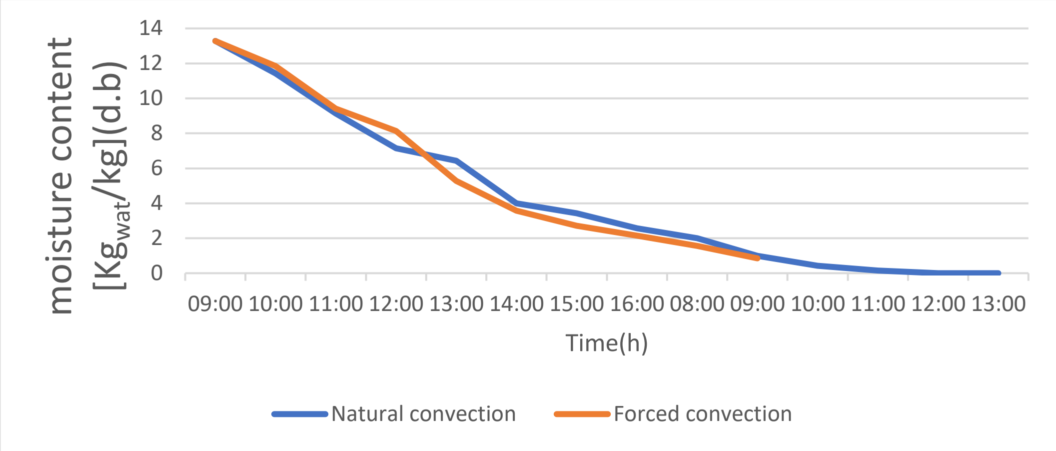


Fig (IV-2d): Variation moisture content (d.b) in solar drying

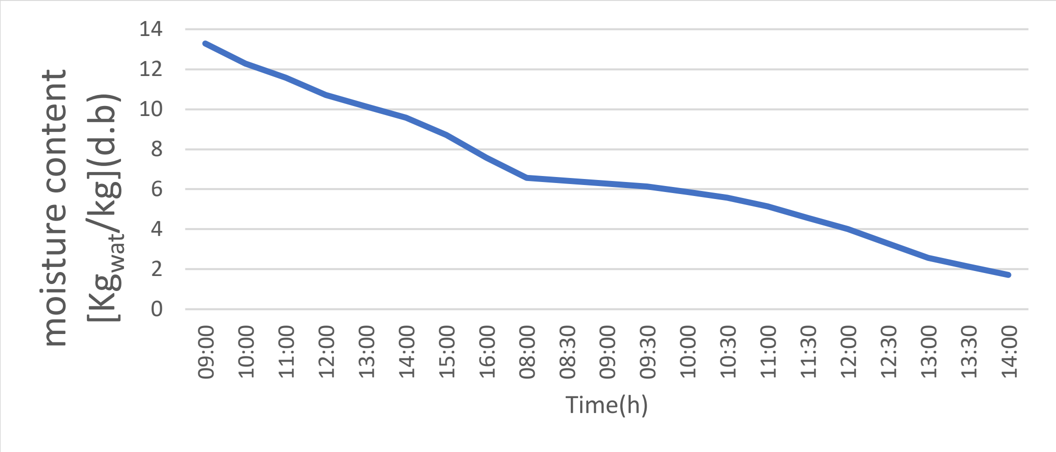


Fig (IV-2e): Variation moisture content (d.b) in natural drying

IV.3. Variation of moisture content (wet basis)

In figures IV-3a to IV-3c we present the variation of the moisture content in time for different air flow rates. It is noticed that for drying temperature T=60°c we lost the maximum water content in the shortest drying time (240min) by using the flow rate 0,003kg/s, On the other hand for drying temperatures 50°c and 40°c the flow rates0,004 and 0,001 was favourable, successively.

In figure IV-3d and IV-3e, we present a comparison between tow solar drying process; forced and natural solar drying. It is noticed that the forced solar drying was faster in the first eight hours; however, in the natural solar drying the moisture content continues to decrease to very low values that we did not obtain by forced drying.

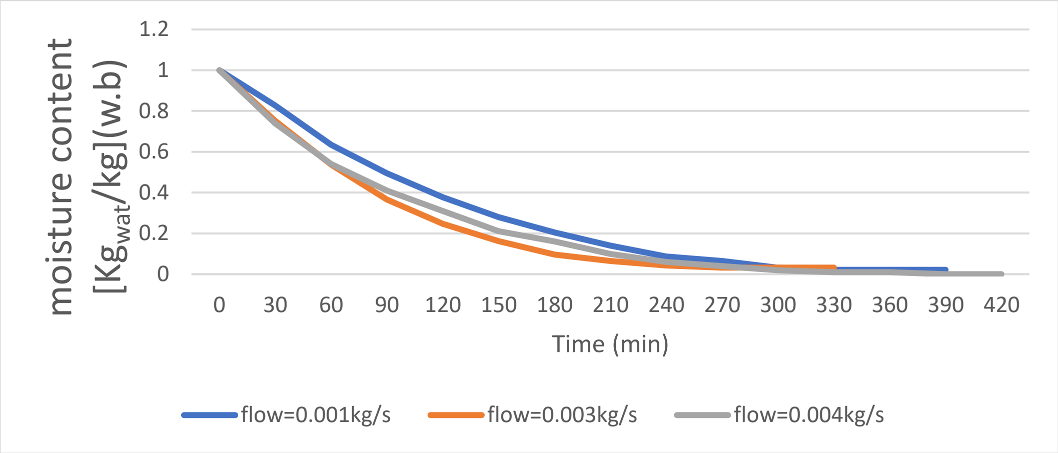


Fig (IV-3a): Variation moisture content (w.b) with 3 different flow (T=60°c)

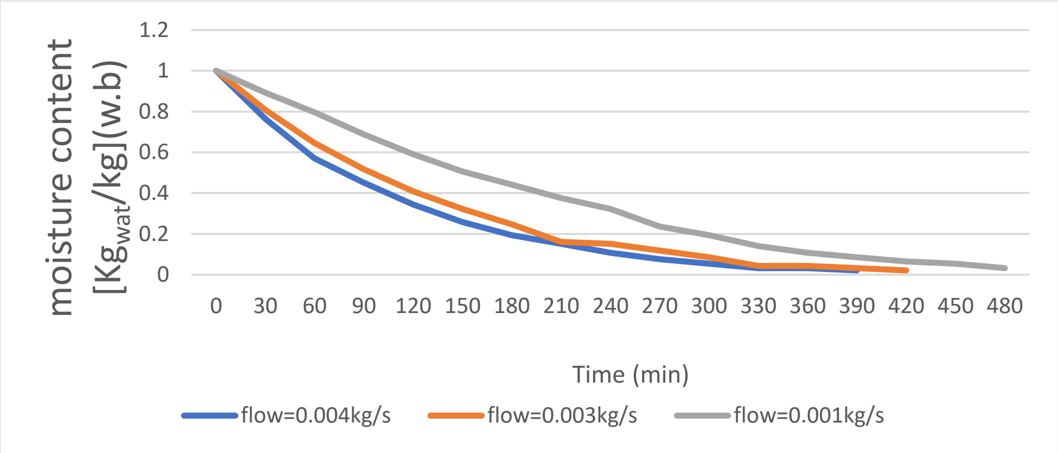


Fig (IV-3b): Variation moisture content (w.b) with 3 different flow (T=50°c)

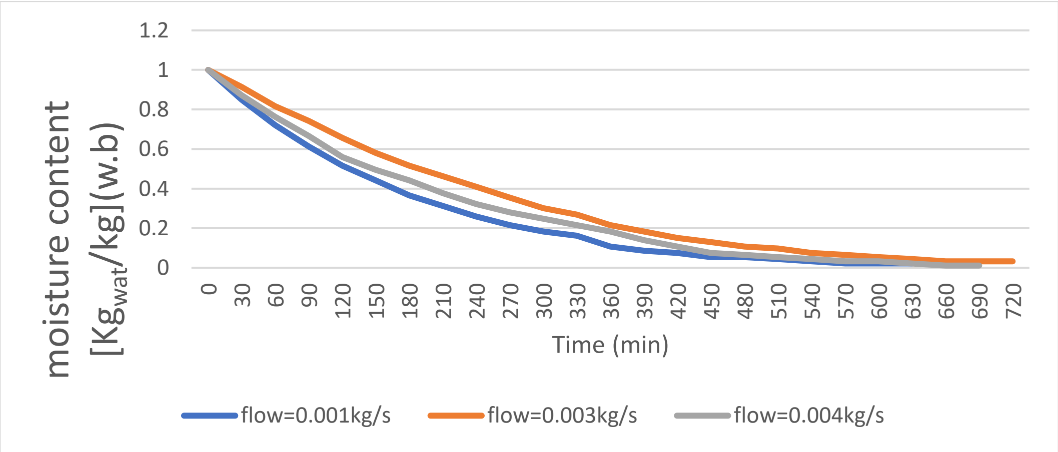


Fig (IV-3c): Variation moisture content (w.b) with 3 different flow (T=40°c)

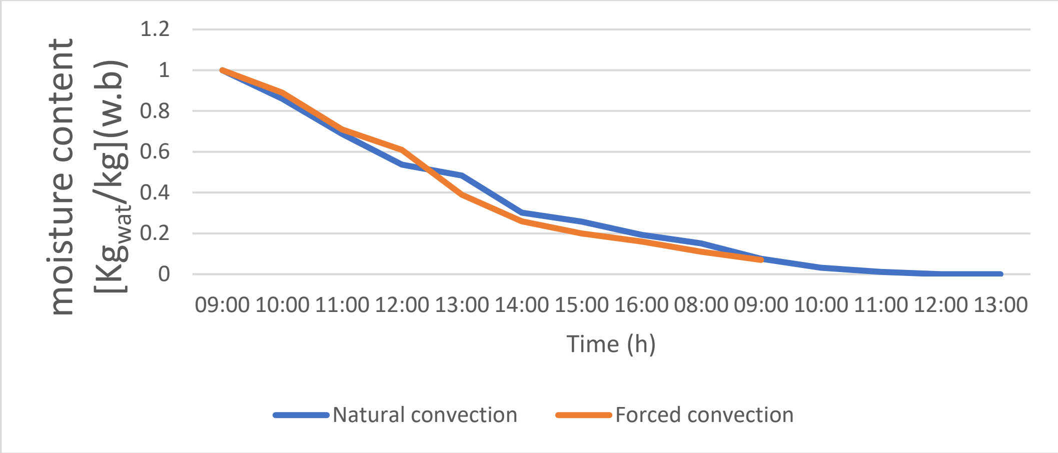


Fig (IV-3d): Variation moisture content content(w.b) solar drying

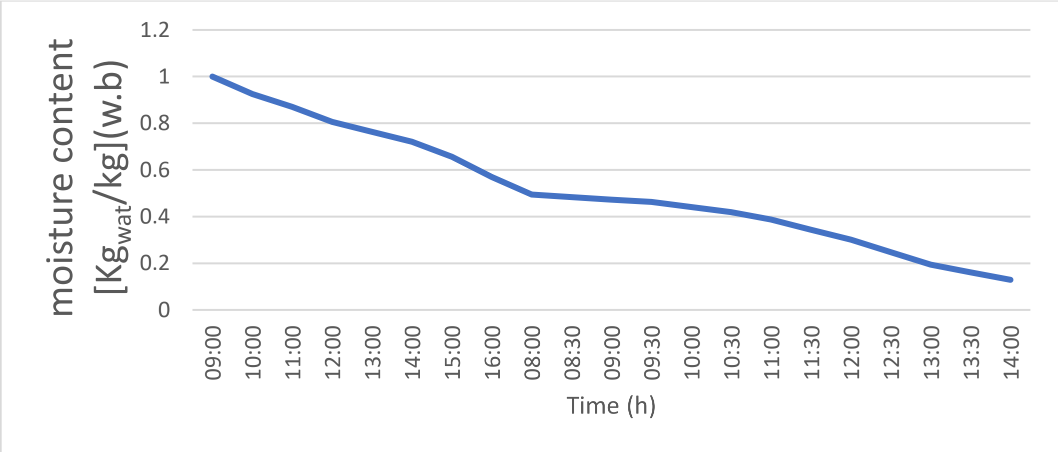


Fig (IV-3e): Variation moisture content (w.b) in natural drying

IV.4. Variation of Loss of mass

Figures IV-4a to IV-4c below, show the curves of variation in loss of mass in temperature 60,50, and 40°c with three different air flow.

The mass loss increases over time until the drying process is finished, and this is what the curves show.

-in fig IV-4a we observed increases in loss of mass where in end of drying they reached 90g ,To lead to a value of mass loss of 90g, the drying time with the first air flow rate (0.001 kg/s) is longer (5 h00 min) but is equal to 4h 30 min with the second, and the third flow rate (0.003 and 0.004 kg/s),

And in fig IV-4b show variation Loss of mass in temperature 50°c with 3 different flow, where in air flow (0.001 kg/s) the drying time is 8h 00 min and equal 6h 30 min ,5h 30min in the other air flow (0.003,0.004kg/s).

While at 40 °C, the fastest drying was at an air flow (0.001kg/s) with a drying time of 9 h 00 min ,As for the air flow 0.004kg/s, the drying time was 9h 30 min and finally at air flow equal 0.003kg/s the drying time was 11h 00min.

Through the previous analysis, it can be observed that the drying time is affected by several factors such as temperature and air flow, and in general, each increase in one of them.

Fig IV-4d and IV-4e show variation of Loss of mass in solar drying and natural drying. It is noticed that, in the end of drying, loss of mass is 86g and 93g in solar drying (natural convection and forced convection, respectively. In an estimated period of time 9h 00min and 13h 00min at Respectively),and 81g in natural drying In an estimated period of time 10 h.

We can noticed is clear that drying with a solar dryer is better than natural drying.

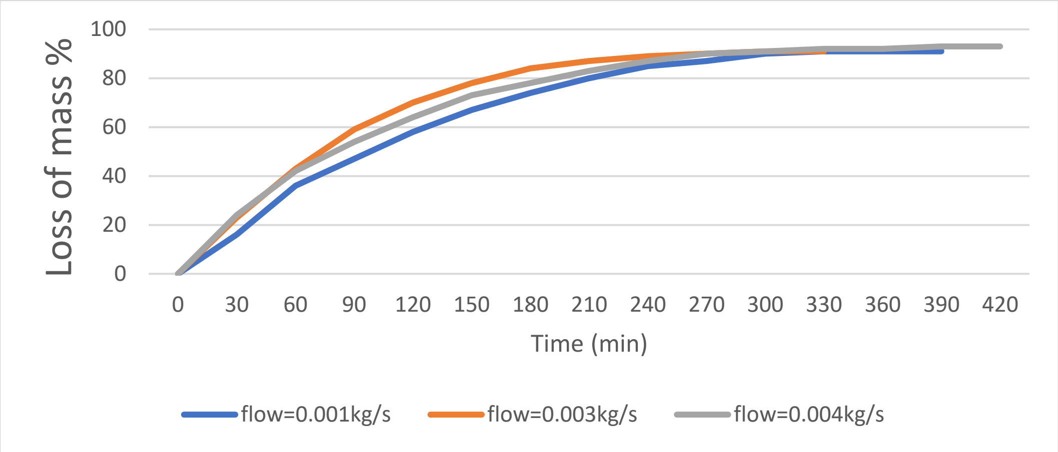


Fig (IV-4a): Variation Loss of mass with 3 different flow (T=60°c)

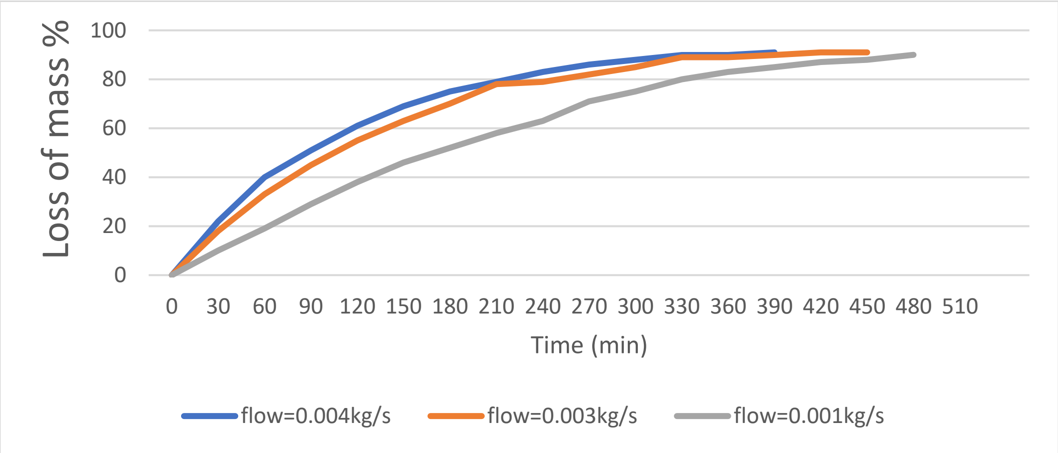


Fig (IV-4b): Variation Loss of mass with 3 different flow (T=50°c)

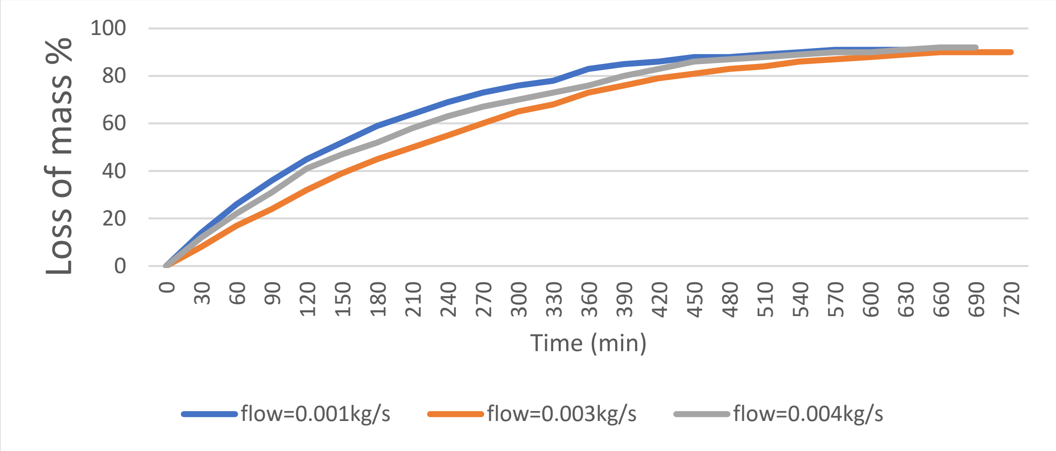


Fig (IV-4c): Variation Loss of mass with 3 different flow (T=40°c)

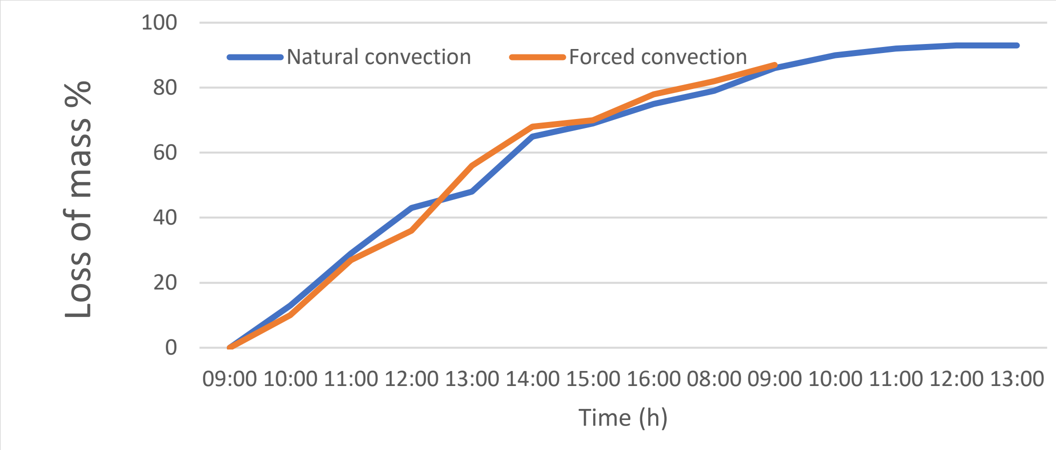


Fig (IV-4d): Variation Loss of mass in solar drying

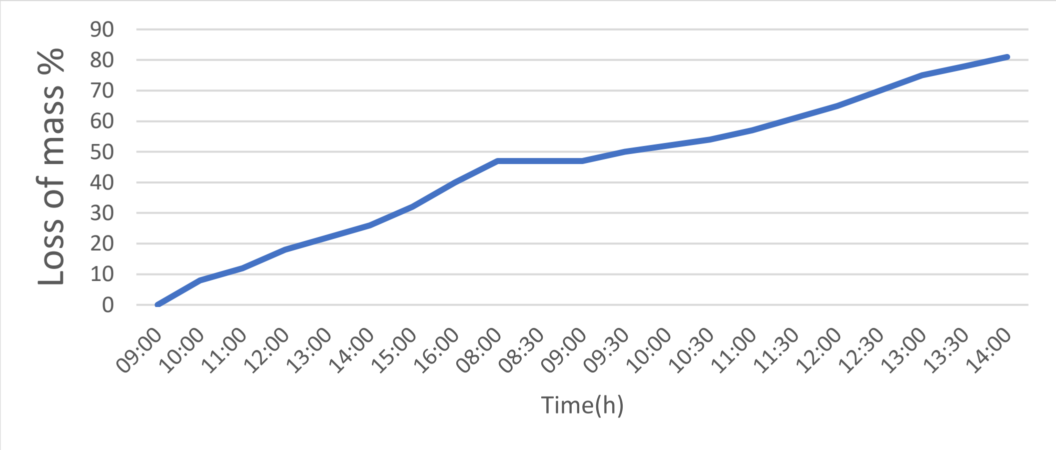


Fig (IV-4e): Variation Loss of mass in natural drying

IV.5. Variation of drying rate

The curves in Figures IV-4a to IV-4e below show the variation of drying rate over drying time. The shape of the curves for drying rate as opposed to usual curves does not contain (ascending/stabilization) phases, it directly begins from a certain value and starts decreasing.

In fig IV-4a we observed at the beginning of drying process, best drying rate (6 , 6.14 Kg_{wat}/kg.h (d.b)) was at the second and third air flows (0.003,0.004 Kg/s at respectively),however, during the middle of the drying process (after 3 h 30min) the situatuation changed a little as the first air flow (0.001 kg/s) became best drying rate (1.57 Kg_{wat}/kg.h (d.b)),but at the end of drying process the third air flow was the best value (0.14 Kg_{wat}/kg.h(d.b)).

In fig IV-4b we see At the beginning of the drying process, the drying rate was highest (5.71 Kg_{wat}/kg.h (d.b)) at the third air flow(0.004kg/s), while in the middle of the drying process the highest drying rate (1.86 Kg_{wat}/kg.h (d.b)) was at the first air flow and continued until the end of the drying process.

In fig IV-4c we noticed during the start of the experiment that the highest value of drying rate was at highest air flow (0.004kg/s) till mid test (6h) .after that, drying rate sit at 0.003 kg/s (highest) , but the end of the experiment, the highest drying rate was at air flow 0.004kg/s.

The fig IV-4d represents a variation of the drying rate of a solar dryer, where we noticed the increase and decrease in both curves, however, after 3 hours the drying rate value was (2.86 Kg_{wat}/kg.h(d.b)) in forced convection curve and (0.71 Kg_{wat}/kg.h (d.b)) in natural convection curve, but after 8 hours drying rate value was (0.72 Kg_{wat}/kg.h (d.b)) for forced convection curve and (1 Kg_{wat}/kg.h (d.b)) for natural convection curve.

Note: The two experiments of solar drying were conducted on two different time periods, where the first experiment(forced convection) was conducted on a partly cloudy day, and the second experiment (natural convection) was conducted on a sunny day. Despite this, we noticed that in many cases, solar drying (forced convection) gives better or at least equal results.

The figure IV-4e shows the variation in drying rate over time, at the beginning of the drying process, we observed a fluctuation in the drying rate (due to the weather) until midday, then after the weather improved, we noticed an increase in the drying rate, reaching a maximum value (1.142 Kg_{wat}/kg.h (d.b)) at 15h 00min, At the beginning of the drying process on the second day, we noticed that the drying rate was stable, then with the passage of time it began to increase till it reached a value of 0.71 at 12h 30min , but after this it began to decrease, reaching in the end to (0.42 Kg_{wat}/kg.h (d.b)) at 14h 00min.

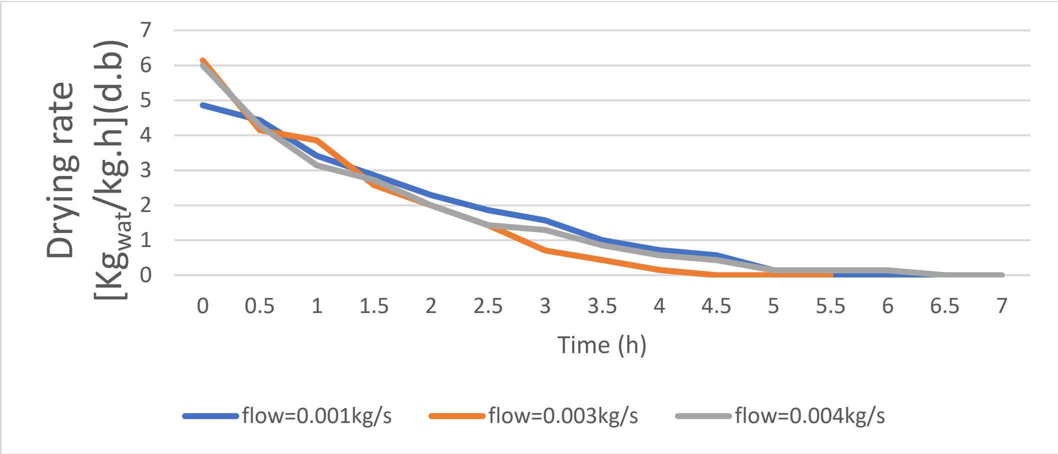


Fig (IV-5a): Variation drying rate with 3 different flow (T=60°c)

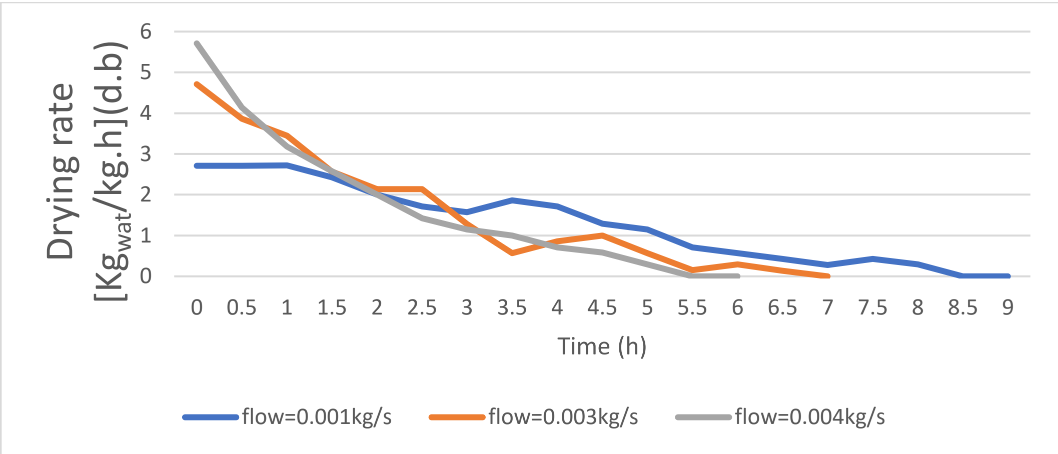


Fig (IV-5b): Variation drying rate with 3 different flow (T=50°c)

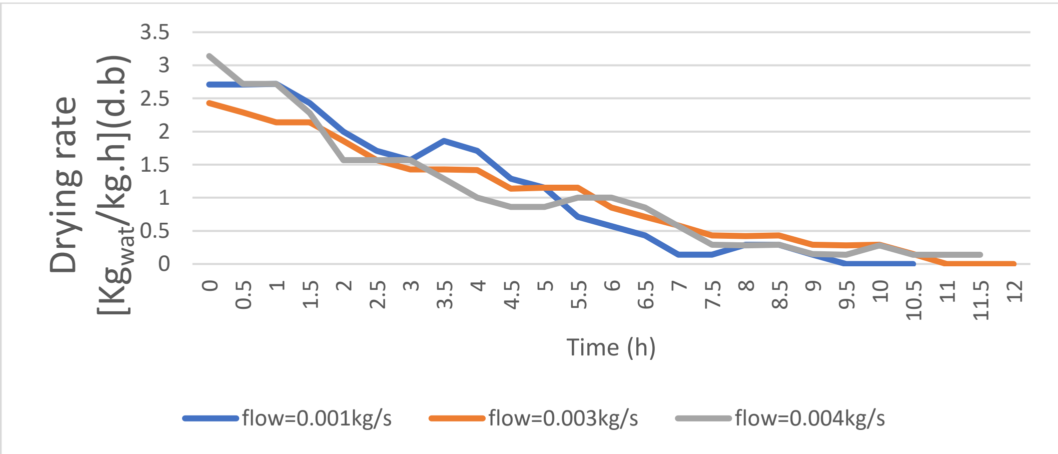


Fig (IV-5c): Variation drying rate with 3 different flow (T=40°c)

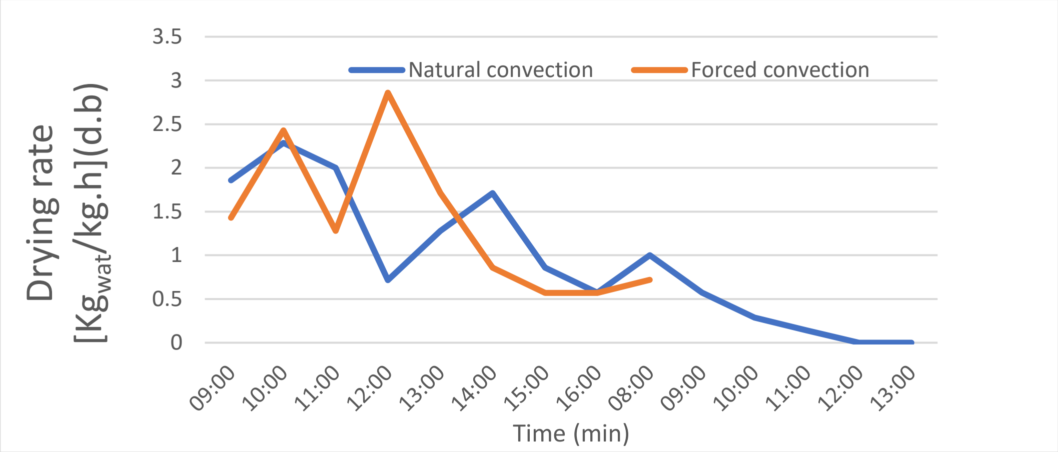


Fig (IV-5d): Variation drying rate in solar drying

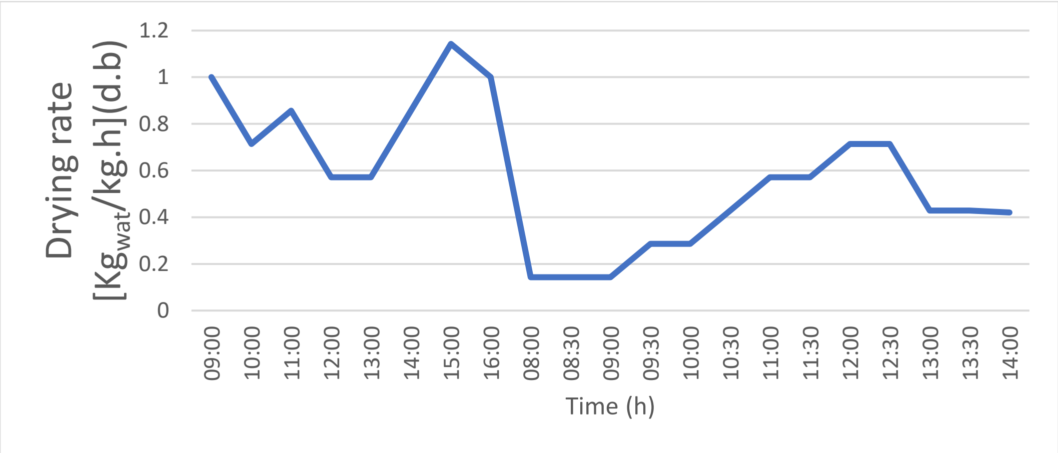


Fig (IV-5e): Variation drying rate in natural drying

IV.6. Conclusion

In this fourth and last chapter, we have seen a set of curves that reflect the most important factors affecting the process of drying.

The main purpose of this chapter was to investigate the various changes that occur on the basic factors from the beginning to the end of the drying process and to provide the appropriate explanations.

The main important result is that, the mass loss increases over time until the drying process is finished, and this is what the curves show.

The forced solar drying was faster in the first eight hours; however, in the natural solar drying the moisture content continues to decrease to very low values that we did not obtain by forced drying.

It is noticed that the shape of the curves for drying rate does not contain (ascending/stabilization) phases, it directly begins from a certain value and starts decreasing.

It is clear that drying with a solar dryer better then natural drying, these factors can contribute to a decrease in the drying time.

General Conclusion

General conclusion

In conclusion, this experimental study mainly has been carried out to investigate the drying behaviour of hot chili under effect of some factors (air flow rate and drying temperature), by using an electric oven, and indirect solar dryer which was designed and constructed previously with local materials in university of Biskra.

Repetitive tests show that the drying time and drying rate are strongly influenced by air flow rate and drying temperature and that confirms the choice of high air flow rate and height drying temperature is always accompanied with drying time faster.

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It is clear that drying with a solar dryer better then natural drying, these factors can contribute to a decrease in the drying time.

For the moisture content (dry basis and wet basis), we noticed that the change in temperature and air flow affects the moisture content and consequently the drying time, and the same thing for loss of mass where we noticed that at high temperatures and high air flow rates the loss of mass is higher.

For the drying rate, we noticed that it is constantly decreasing until it is absent in some cases. This is for the oven drying, however, for solar drying (natural convection and forced convection) and sun drying (under open air drying), we noticed that the drying rate goes through two stages, it increases in first stage and decrease in the second stage.

ملخص:

هدفت دراستنا التجريبية إلى التحقق من سلوك تجفيف الفلفل الحار (تحت الحمل الحراري الطبيعي والقسري) باستخدام فرن التجفيف والمجفف الشمسي غير المباشر و الذي تم تصميمه وإنشاؤه مسبقًا بمواد محلية بالاضافة الى التجفيف الشمسي الطبيعي. تركز هذه الدراسة على تجفيف الفلفل الحار ، حيث قمنا بتقطيعه إلى شرائح دائرية صغيرة .

النتائج التي تم الحصول عليها وتحليلها تقودنا إلى الاستنتاج التالي:

بشكل عام ، تؤثر درجة حرارة التجفيف ومعدل تدفق الهواء على عملية التجفيف ، حيث تؤدي كل زيادة في أحد هذين العاملين إلى تقليل وقت عملية التجفيف.

الكلمات المفتاحية: التجفيف ، الحمل الحراري الطبيعي و القسري، مجفف شمسي، فرن تجفيف، فلفل حار.

Abstract

Our experimental study aimed to investigate the drying behavior of hot chili (under natural and forced convection) using a drying oven and an indirect solar dryer, which was designed and constructed previously with domestic materials.

The results obtained and analyzed lead us to the following conclusion:

In general, the drying temperature and air flow rate affect the drying process, as each increase in one of these two factors leads to a decrease in the time of the drying process.

Keywords: drying, natural and forced convection, solar dryer, drying oven , hot chili.

Résumé :

Notre étude expérimentale visait à étudier le comportement de séchage du piment (sous convection naturelle et forcée) à l'aide d'un four de séchage et d'un séchoir solaire indirect, qui a été conçu et construit auparavant avec des matériaux domestiques. Cette étude se concentre sur le séchage des piments verts, coupés en petites tranches circulaires.

Les résultats obtenus et analysés nous amènent à la conclusion suivante :

En général, la température de séchage et le débit d'air affectent le processus de séchage, car chaque augmentation de l'un de ces deux facteurs entraîne une diminution de la durée du processus de séchage.

Mots clés: séchage, convection naturelle (libre) et forcée, séchoir solaire, etuvé de séchage**,** piment vert