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THEME

Design and Experimental Analysis Of a Direct Solar Dryer With Thermal Energy Storage Equipped With a New Heat Recovery System.

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Dedications

"The journey was not short, and it shouldn't have been. The dream was not close, and the road was not paved with facilitations, but I did it.

I dedicate my graduation to the one whose name I proudly carry, to the one who cleared the thorns from my path, paving the way for knowledge, to ***"my dear father"****. After the grace of God, everything I have achieved is thanks to my father, the man who did not receive even a small portion of what we have achieved, and the man who strived all his life for us to be better than him. I pray to God to grant you a long life.*

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And I dedicate my graduation to the soul of my niece's son ***"Nizar"*** *We ask Allah to compensate for his childhood in paradise, and to inspire my sister, the delight of my eyes, with patience and solace. I will never forget you, my angel.*

Finally, we ask Allah for success in our lives.

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I DEDICATE THIS WORK

TO MY FAMILY, WHO GAVE ME A WORTHY EDUCATION, THEIR LOVE MADE ME WHAT I AM TODAY:

PARTICULARLY TO MY BELOVED **FATHER FAYÇAL**, FOR THE TASTE OF EFFORT HE AROUSED IN ME, BY HIS RIGOR.

TO MY DEAREST PERSON, TO **MY MOTHER**, THIS IS MY DEEP GRATITUDE FOR YOUR ETERNAL LOVE, MAY THIS REPORT BE THE BEST GIFT I CAN GIVE YOU.

TO YOU MY SISTERS (DOUAA, NADA, FARAH, AND THE LOVELY CUPCAKE **TAKWA**) WHO HAVE ALWAYS SUPPORTED AND ENCOURAGED ME DURING THESE YEARS OF STUDY.

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TO MY SECOND FAMILY IRFANE STUDENT ASSOCIATION IN MOGGAR

...Abd El Mouaz Djaber Guessoum

Summary:

This postgraduate thesis investigates the performance of two preliminary models of natural convection solar dryers, one equipped with a heat recovery system and the other without this system. The aim of the study is to enhance the efficiency of solar dryers by addressing the challenge of insufficient solar energy during certain periods. To overcome this limitation, a heat recovery system was integrated to reduce heat loss, and the dryers were equipped with paraffin wax (PCM) boxes for thermal energy storage, enabling effective drying even under low solar energy conditions. Experimental tests were conducted at the Applied Renewable Energies Research Unit (URAER) in Ghardaia, under real weather conditions.

The initial models were subjected to no-load tests, and the internal air temperature reached 87 degrees Celsius in the solar dryer with the heat recovery system, and 65 degrees Celsius in the solar dryer without the heat recovery system. The average absorber temperatures were recorded as 75 degrees Celsius in the dryer with heat recovery and 66 degrees Celsius in the dryer without heat recovery. Performance evaluation of natural convection greenhouse dryers was conducted using peppers as drying products. Ten mathematical models were used to describe the drying kinetics of the thin layer of peppers.

The results indicated that the **Logarithmic** and **Midilli-Kucuk** models were the most suitable for describing the solar drying process of the products in the tested preliminary models.

The moisture content of the peppers decreased from **93%** to **11%** within a period of three to four days. The dryer with the heat recovery system resulted in faster drying up to one day and a gain in drying temperature approximately 30% up to 20 degrees.

The efficiency of the preliminary models was determined to be **40%** for the dryer with heat recovery and **30.76%** for the second dryer without heat recovery.

Overall, this study demonstrates the potential of integrating heat recovery and thermal energy storage systems into solar dryers to improve their performance during periods of low solar energy availability. The results provide valuable insights for improving the design and operation of solar greenhouse dryers for effective drying of agricultural products with reduced energy consumption.

ملخص :

تبحث مذكرة التخرج هذه في أداء نموذجين أوليين من المجففات الشمسية ذات الحمل الحراري الطبيعي ، أحدهما مزود بنظام إعادة تدوير الحرارة والآخر غير مزود بهذا النظام . الهدف من الدراسة هو تعزيز كفاءة المجففات الشمسية من خلال مواجهة التحدي المتمثل في عدم كفاية الطاقة الشمسية خلال فترات معينة. للتغلب على هذا القيد ، تم دمج نظام إعادة تدوير الحرارة لتقليل فقد الحرارة ،كما تم تزويد المجفف بعلب من البرافين (pcm) لتخزين الطاقة الحرارية وبالتالي تمكين التجفيف الفعال حتى في ظروف الطاقة الشمسية المنخفضة. تم إجراء الاختبارات التجريبية في وحدة أبحاث الطاقات المتجددة التطبيقية (URAER) في غرداية ، في ظل ظروف جوية حقيقية.

تم إخضاع النماذج الأولية لاختبار عدم التحميل ، ووصلت درجة حرارة الهواء الداخلي إلى 87 درجة مئوية في المجفف الشمسي المزود بنظام اعادة التدوير و 65 درجة مئوية في المجفف الشمسي الغير مزود بنظام إعادة التدوير . تم تسجيل متوسط درجات حرارة الامتصاص في المجفف الشمسي مع اعادة التدوير بـ 75 درجة مئوية و المجفف بدون اعادة التدوير 66 درجة مئوية على التوالي. تم إجراء تقييم أداء مجففات الدفيئة بالحمل الحراري الطبيعي باستخدام الفلفل كمنتجات تجفيف. تم استخدام عشرة نماذج رياضية لوصف حركية تجفيف الطبقة الرقيقة للفلفل.

أشارت النتائج إلى أن نموذج **Logarithmic** ونموذج **Midilli-Kucuk** هما الأنسب لوصف عملية التجفيف الشمسي للمنتجين في النماذج الأولية التي تم فحصها.

انخفض المحتوى الرطوبي للفلفل من 93٪ إلى 11٪ خلال فترة ثلاثة إلى أربعة أيام. نتج عن المجفف المزود بنظام استرداد الحرارة تجفيف أسرع يصل إلى يوم واحد وزيادة درجة حرارة التجفيف حتى 20 درجة المقدرة ب **30.76**٪

بشكل عام ، توضح هذه الدراسة إمكانية دمج نظام إعادة تدوير الحرارة وتخزين الطاقة الحرارية في المجففات الشمسية لتحسين أدائها خلال فترات انخفاض توافر الطاقة الشمسية. توفر النتائج رؤى قيمة في تحسين تصميم وتشغيل مجففات الدفيئة الشمسية من أجل التجفيف الفعال للمنتجات الزراعية مع تقليل استهلاك الطاقة.

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Chapter I : Generalities On The Different Drying Technique

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Nomenclature

Latin-alphabet

m	Mass	Kg
Cp	Specific Heat	$J.kg^{-1}.k^{-1}$
T	Temperature	K
Lf	Latent Heat of Fusion of MCP	$J.kg^{-1}$
Q	Sensible Heat	$kg.s^{-1}$
$\dot{m}$	Mass Flow Rate	kg.s−1
MR	Reduced Moisture Content	Kg of water/Kg of dry matter
MR_0	Initial Moisture Content	Kg of water/Kg of dry matter
MR_{eq}	Equilibrium Moisture Content	Kg of water/Kg of dry matter
MR_{pred}	Predicted Moisture Content	Kg of water/Kg of dry matter
MR_{exp}	Experimental Moisture Content	Kg of water/Kg of dry matter
HR	Relative Humidity	%
Q	Useful Energy	W
W	Absolute Humidity of Air	Kg of water/Kg of dry air
P_V	Partial Pressure of Water Vapor	Pa
P	Partial Pressure of Air	Pa
RMSE	Root Mean Square Error	-
N	Number of observations	-
n	Number of Model constants	-
t	Time	s

D_{eff}	Effective Diffusivity	m2/s
L	Half Thickness of Slice	m
A_c	Area	m^2
I	Solar Radiation Intensity	W/m^2

Greek Alphabet

Δ	Variation
η	Thermal efficiency
τ_c	Cover transmissivity
χ^2	Minimum reduced chi-square

Indices

PCM	Phase Change Material
PC	Polycarbonate
URAER	Applied Research Unit in Renewable Energies

General Introduction

General Introduction:

The increase in energy demand worldwide is driven by the growth of economies and countries' energy needs. Extensive research indicates that the global energy supply doubles every 20 years. However, this increased energy consumption has given rise to numerous environmental problems and pollution due to the heavy reliance on fossil fuels. With fossil fuel resources steadily depleting due to the growing use of electricity, heating, refrigeration, and air conditioning, researchers have turned their attention to renewable energy sources such as solar, wind, oceanic, and geothermal energy. Despite the potential, renewable energy utilization remains lower than fossil fuels **[1]**.

Nevertheless, there has been a recent upswing in the willingness to adopt renewable and new energies, particularly solar energy. Solar energy, renowned for its direct usability, continuous availability, safety, cost-effectiveness, and environmental friendliness, has been employed for various purposes over the years, including drying clothes, fish, and agricultural products. However, drying operations pose a significant energy-intensive challenge as the latent heat associated with product moisture must be eliminated using hot air. Various energy sources, such as LPG, coal, biomass, and solar energy, are employed to meet the energy requirements of drying operations. Solar energy stands as the most widely used renewable energy source in drying processes, having been harnessed by humanity for many decades. Although traditional outdoor drying represents the most significant solar energy application and a cost-effective drying technique, it is fraught with limitations such as extended drying times, contamination risks, lack of process control, loss of natural colors and minerals, susceptibility to product damage by insects, birds, and adverse weather conditions, large space requirements, and high labor costs. Solar dryers have been developed to overcome these limitations associated with open-air drying. These dryers facilitate the drying of products within enclosed spaces or drying cabinets at elevated temperatures, offering a more efficient alternative to direct sun drying. Compared to open sun drying under the same solar radiation intensity, solar dryers enable drying at higher temperatures and lower relative humidity, providing a more suitable drying environment for various agricultural products within a drying air temperature range of 45 °C to 60 °C. However, concerns related to the intermittent nature and uncertainty of solar radiation availability persist, affecting the reliability and widespread adoption of solar dryers. To address these challenges, auxiliary heat sources such as electric, biomass, and LPG stoves are typically integrated into solar dryers. Additionally, thermal storage systems are incorporated into solar dryers to supply the necessary heat during periods of cloud cover or inadequate solar radiation. Sensible heat storage (SHS) and latent heat storage

(LHS) are the two primary types of thermal energy storage modules employed in solar dryers. SHS involves raising the temperature of storage materials such as stone, rock, sand, concrete, pebbles, and water to store thermal energy. In contrast, LHS utilizes phase change materials (PCM) such as paraffin wax and hexahydrate calcium chloride to store thermal energy through the phase transition of the storage material from solid to liquid. The application of LHS in solar dryers has gained significant attention due to its numerous advantages, including high energy storage capacity, dissipation of energy at a nearly constant temperature, and low volume-to-mass ratio. While many researchers have explored various types of direct solar dryers, such as tunnel and trapezoidal designs, none have investigated a direct solar dryer equipped with an integrated thermal storage device and a new heat recovery system .

Research objectives:

The general objective of this work in conducting an experimental and mathematical study of a novel solar dryer design that integrates paraffin wax as PCM for a thermal energy storage system and incorporates a new heat recovery system. The experimental setup is conducted at the Applied Research Unit for Renewable Energies (URAER) in Ghardaïa, situated at a latitude of 32.37° North and a longitude of 3.77 West.

Specific research objectives:

The specific objectives of this research were:

1. To develop new-design direct-type solar dryers by integrating a phase change thermal energy storage device equipped with a new heat recovery system;
2. To evaluate the performance of direct-type solar dryer prototypes using various parameters such as dryer temperature and product moisture content;
3. To compare the performance of direct-type solar dryer prototypes with different improvements made;
4. To fit drying curves to ten mathematical models

This research has important value for future investigations on integrating phase change materials (PCM) in direct solar dryers. The first chapters of this thesis give an overview of drying techniques used in different applications, followed by a review of scientific literature on the discussed concepts. Chapter 3 explains the methodology used in this study, detailing the design and evaluation of the storage device integrated into the prototype of a direct-type solar dryer. Chapter 4 includes a thorough analysis and discussion of the experiment's results;

Chapter I :

Generalities On The Different Drying Technique

I.1 Introduction:

drying is the process of removing moisture from products. It is a very important process applicable to agricultural and industrial products. Drying reduces bacterial growth in products and helps to preserve them for a longer period of time. Drying is generally considered the oldest and most commonly used technique for food preservation. Open-air sun drying is a traditional and inexpensive method of preservation, but the disadvantage of this method is the deterioration of the harvest due to ultraviolet rays, dust particles, and abiotic factors such as insects, animals, and microorganisms that do not meet international standards.

although sun drying is a popular method of drying crops, it is a slow drying process with the risk of mold growth causing the deterioration of dried products depending on weather conditions. It also requires a significant amount of labor and is highly exposed to potential environmental contamination. Therefore, to avoid these drawbacks, it is necessary to use other solar drying methods.

the different methods of solar drying include direct solar drying, indirect solar drying, and mixed-mode solar drying. The device used for the solar drying process is called a solar dryer. Solar dryers are also classified by the mode of air circulation. In this chapter, we have studied the different modes of solar drying and the classification of solar drying techniques **[2].**

I.2 Definition of drying:

drying is an operation aimed at partially or completely removing water from a wet substance by evaporation of this water. This operation involves a transfer of heat (the supply of heat allows the liquid to change phase) and a transfer of mass (the liquid impregnating the solid changes to vapor in the drying air). The product to be dried can be solid or liquid, but the final product is always solid [**3**]. The objective of drying a product is to reduce its water content, so that its water activity is reduced to a value that allows it to be stored at normal temperature for long periods (of the order of one year). The objectives sought through this drying are :

- To create reserves in order to market the product during shortages and to spread out the consumption of the product (increase the shelf life of products);

- To transform unsold products;

- To transport and market more easily (the cost of transport is higher in the presence of liquid). However, this operation always involves changes in taste, appearance and loss of nutritional quality or hygiene of the product [**4**].

I.3 Field of application:

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

Food industry:

A large part of the food we consume undergoes a drying process. Drying can be a necessary step in the production of a product or play 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;
- Cheese: drying in a controlled environment;
- Crystallized sugar is obtained by evaporation;
- Vegetables (peas, etc..) and dried fruits (prunes, raisins, apricots, etc..);
- Some appetizer 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;
- Drying ensures the preservation of many types of grains or vegetables, such as coffee, cocoa, rice and other cereals, tea leaves, spices, etc..;
- Some powdered products: cocoa, milk, etc..

Paper industry:

Paper is obtained by drying the paper pulp on heated rotating rollers.

Wood industry:

Freshly cut and sawn wood contains a high degree of moisture that prevents its immediate use under correct conditions, otherwise we expose ourselves to changes in size and shape of the wood.

Cork stoppers:

To guarantee the best aging of wines, special attention is paid to the quality of cork stoppers. During their production, the drying process must be perfectly controlled, otherwise the wine may have a musty taste.

Construction materials:

- Bricks, tiles, etc.

Ceramic industry:

- Plates, bowls, dishes, etc.

Biotechnology and pharmaceutical industry:

- Powdered yeast;
- Antibiotics;
- Drying of active ingredients in powder form before pastillation;
- Drying of cores which ensure the elaboration of the internal shapes of the parts obtained by molding **[5].**

I.4 Drying Mechanism :

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

1) Heat transfer to provide the latent heat of vaporization required;

2) The movement of water or water vapor through the wet product to extract it from the products.

A wet product can be schematically represented as shown in **Figure I.1**. The solid has a film of water adhering to its external surface by surface forces.

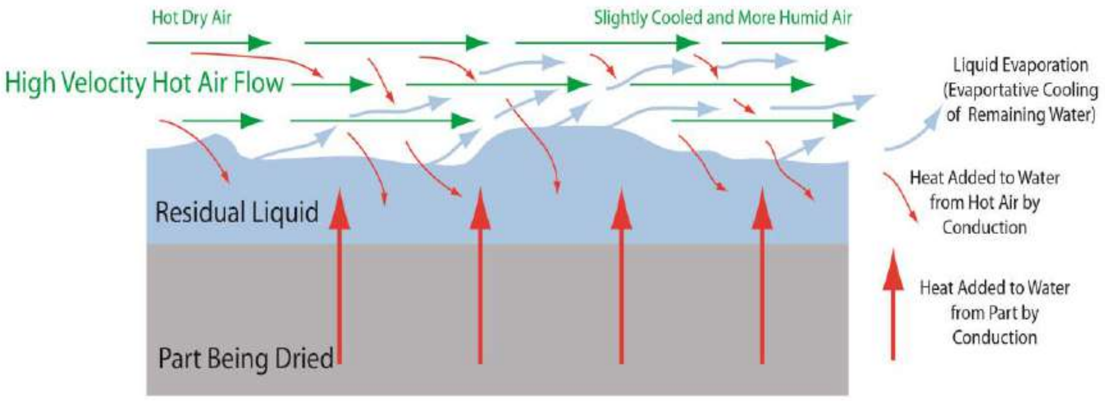


Figure I. 1 Schematic representation of a wet product [4] .

Upon contact with the hot air, the water from the external surface of the product will be evacuated due to the humidity gradient between the air and the product. Osmotic water will migrate in a liquid state from the interior of the grain to this periphery dried by osmotic pressure difference. During this migration, pockets of air appear to replace water losses. During drying, cell-to-cell diffusion will be increasingly inhibited by cells that tend to retain their water. The last points of moisture will therefore be more difficult to remove than the first ones. Liquid water will be completely evaporated except for strongly retained water. The product returns to hygrometric equilibrium with its environment; this corresponds to the end of drying.

To dry properly, it is necessary to control three fundamental parameters:

- ✓ The thermal energy supplied, which heats the product and causes the water to migrate to the surface and transform into water vapor.
- ✓ The capacity of the surrounding air (also called entrainment air) to absorb the water vapor released by the product. This capacity depends on the percentage of water vapor already contained in the air before entering the dryer and the temperature to which it has been brought.
- ✓ The speed of this air at the product level, which, especially at the beginning of drying, must be high (up to a certain limit) to accelerate the entrainment of water vapor. It is necessary to be able to dry quickly enough (to avoid product rotting), but not too quickly (a crust may form on the surface) at too high a temperature (the product denatures and turns black) **[6]** .

I.5 Solar dryers:

Solar dryers are simple devices that collect solar radiation and concentrate it in the form of thermal energy. This thermal energy is then transported to the product for dehydration. Solar dryers can increase the dehydration temperature and reduce relative humidity, thus lowering the moisture content of dried products. Unlike sun-drying in the open air, solar dryers have a dedicated structure that regulates the dehydration process and protects the product from damage caused by dust, rain, and insects **[7][8].** Since the products are protected and the dehydration time is significantly reduced, the quality of products dried by solar dryers is better than that of products dried in the sun **[9, 10] .** Solar dryers can be classified according to their heating methods or operating systems. Categories of solar dryers include direct dryers, indirect dryers, mixed-type dryers, greenhouse solar dryers, hybrid solar dryers, and solar dryers with energy storage systems.

I.6 Principle of solar dryers:

A solar dryer is a device that transfers heat from a heat source to a product and transfers the mass (moisture) from the surface of the product to the ambient air **[11] .**The basic function of a solar dryer is to increase the vapor pressure of the moisture present inside the product and to increase the moisture transport capacity of the drying air by decreasing its relative humidity **[12].** During solar drying, the hot air captures the moisture from the dried product **[13].** The amount of moisture removed depends on the temperature of the hot air (as it has a higher capacity to capture moisture than cold air). **Figure I.2**[**7**] shows a diagram that explains the general principle of a solar dryer [**14**].

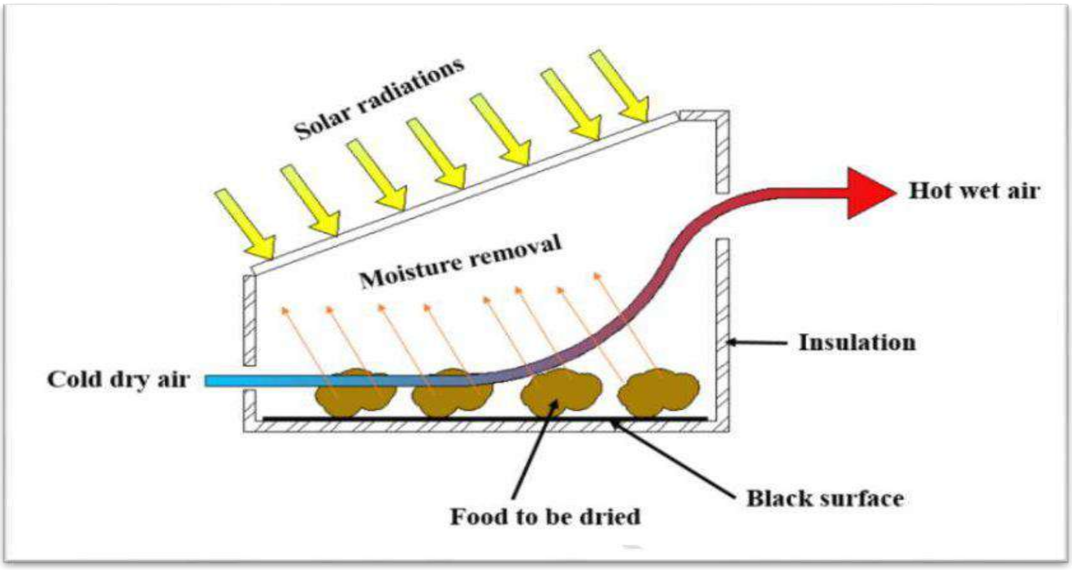


Figure I.2 The principale of a solar dryer [7]

I.7 Components of solar dryers:

Generally, a solar dryer is composed of three main components, which are the drying chamber, the air heater, and the air circulation system. The drying chamber is where the dried foods are placed. It protects the foods from dust and dirt. In most cases, it is insulated to increase the efficiency of drying. The air solar collector is a dark-colored box with a transparent cover. It heats the drying air by increasing the ambient temperature by 10 to 30 °C. Meanwhile, the air circulation system evacuates the humid air to the environment **[14].**

I.8 Main factors of solar drying:

Solar drying systems can be divided into two types, direct and indirect. Also, these systems can be active or passive. There are three main factors that affect food drying: temperature, air flow rate, and humidity, and they are interdependent. There is a diversity of opinion on the ideal drying temperatures, but all reviewed opinions agree on drying temperatures between 35 and 82 °C, with temperatures of 43.5 to 60 °C being the most common **[15].**

1/ Air flow rate:

In natural convection, it is proportional to the surface area of the exhaust opening, the size of the collector (from the air inlet to the air outlet), and the temperature of the absorber plate. However, the air flow rate is also inversely proportional to the temperature in a solar dryer. In the best-case scenario, the aim is to have both high temperature and air flow rate. This can be challenging to achieve in a solar dryer.

2/ Air velocity:

In a natural convection collector, it is affected by the distance between the inlet and outlet of the air, the temperature inside the dryer, and the exhaust air section. The greater the length, temperature, and exhaust section, the greater the velocity.

3/ Relative humidity:

This is the third factor affecting the solar drying of food. The higher the relative humidity, the slower the drying. Each 15 °C increase in temperature doubles the air's capacity to absorb moisture. In humid regions, drying takes longer than in dry regions. The temperature achieved in a dryer will be affected by several factors: the surface of the transparent cover facing the sun, insulation, air tightness, the surface of the exhaust passage, and ambient temperature. The surface of the transparent cover facing the sun is an important design decision.

I.9 Advantages of solar dryer:

- Higher temperature, air movement, and lower humidity increase the drying rate.
- Food is enclosed in the dryer and protected from dust, insects, birds, and animals.
- Higher temperature discourages insects and the faster drying rate reduces the risk of deterioration by microorganisms.
- Higher drying rate also provides higher food throughput and a smaller drying area (about one third).
- Dryers are waterproof, so food does not need to be moved when it rains.
- Dryers can be built from locally available materials and are relatively inexpensive [**15**].

I.10 Classification of solar dryers:

Solar dryers are generally classified into two main categories: passive dryers (natural convection) and active dryers (forced convection). Under each category, three families of solar dryers are effective depending on how solar radiation energy reaches the product to be dried, namely, direct solar dryers, natural indirect and hybrid dryers, and mixed dryers [**16**] **Figure I.3 [17].**

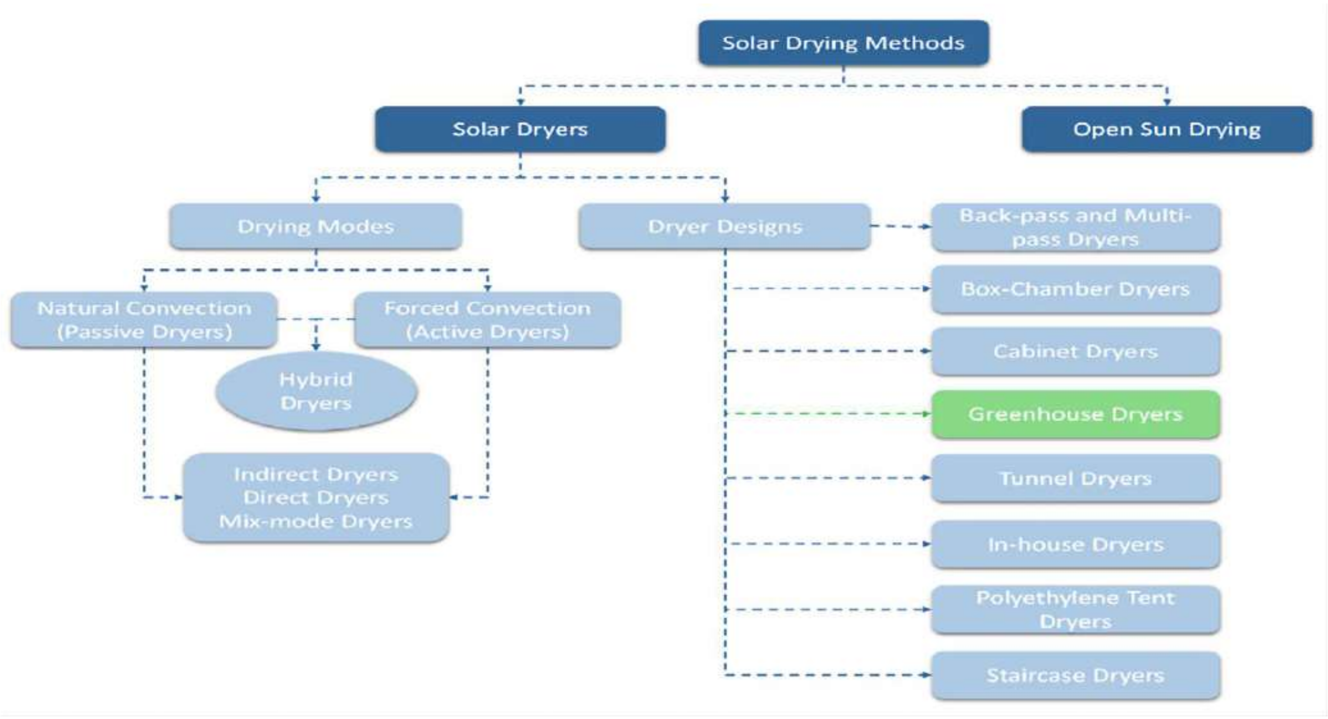


Figure I.3 Categorization of solar-powered dryers [17].

I.10.1 Passive solar dryers:

Passive solar dryers rely on the natural movement of air due to buoyancy, differences in wind pressure, or a combination of these factors. Therefore, this type of dryer is known as a natural convection solar dryer. These solar dryers have a slow drying rate due to the slow movement of air **[18].**

I.10.2 Active solar dryers:

Active solar dryers require fans to channel air through the dryer components that can be mounted at the inlet or outlet. It has a higher drying rate compared to the passive mode, but it requires electrical energy to drive the fan **[19] .**

"The main types of solar-powered dryers are illustrated in the following figure:"

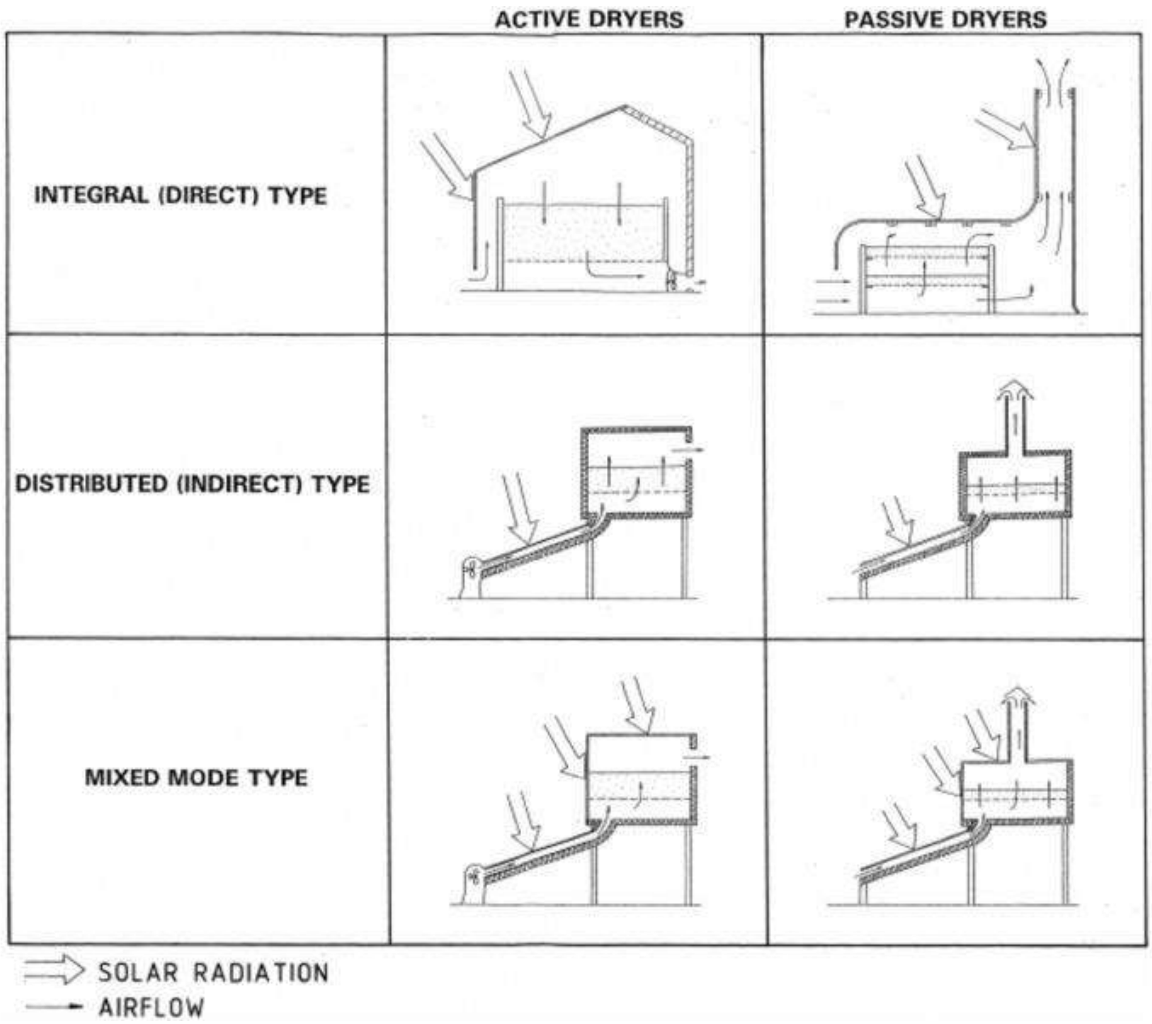


Figure I.4 Presentation of the different functioning modes and types of solar dryers [17].

I.10.3 Natural dryers :

They use direct sunlight and air, where the products are spread out on racks or mats, in cribs, or even laid out on the ground. (The principle of drying in the open air is simple: solar radiation falls on the surface of the crop and part of the energy is reflected back into the environment).

These dryers are very inexpensive, but require regular human intervention, protection or collection of the product in case of rain, frequent mixing to prevent overheating of the top layer and to homogenize the product to allow the lower layer to dry. This type of dryer is often traditional in rural communities to address temporary product preservation issues while awaiting sale or consumption. However, it has disadvantages, including loss of poorly dried or spoiled product during stirring, destruction of vitamin A and C by direct exposure to sunlight, and degradation by weather and pests **[4**] **[4]**. **Figure I.5 [16]** .

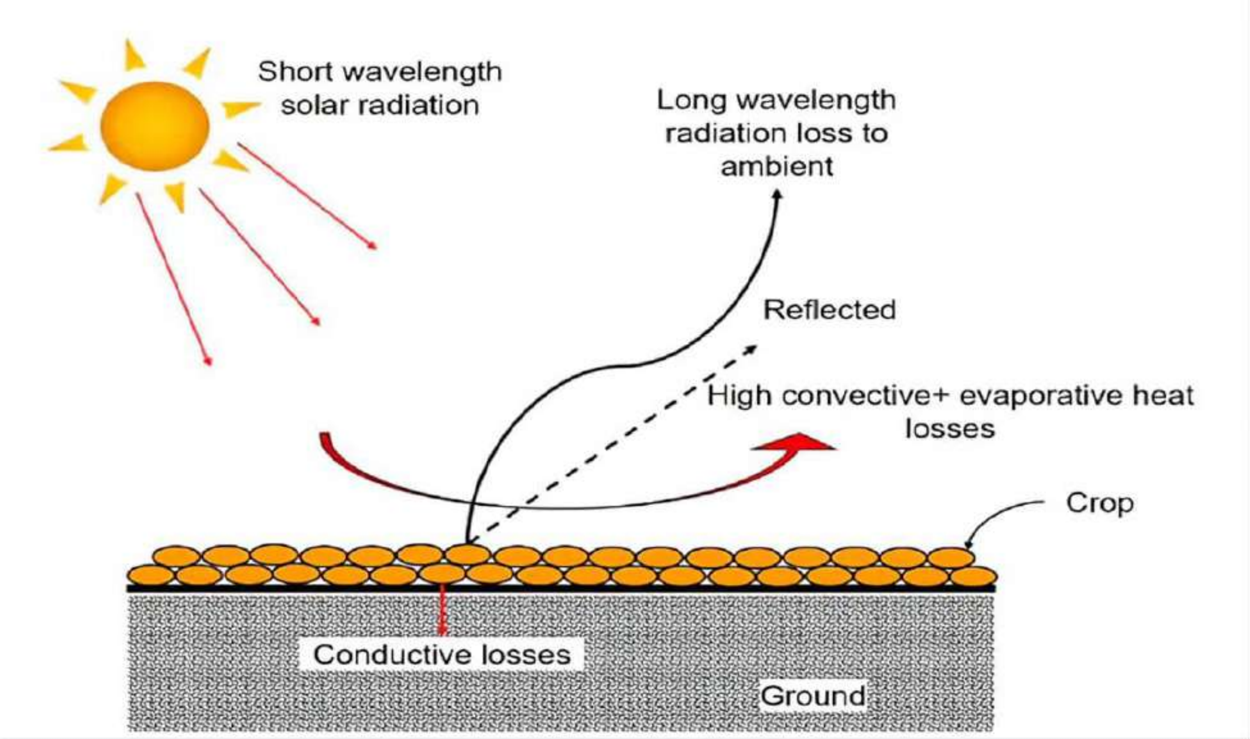


Figure I.5 Sun drying Or Open air Drying [16].

Table I.1 Advantages and disadvantages of natural dryers [4]

Advantages	Disadvantages
•It is a type of drying that does not require any specific equipment. •It is a slow drying process at low temperature that produces wood with minimal stress. •It uses free energy: the sun.	•The method does not allow the moisture content to drop below 13 to 17%. •The wood stock immobilization time is lengthy. •There is a risk of wood being attacked by insects and fungi.

I.10.4 Direct solar dryers :

In these dryers, the sun's rays directly hit the product. They are simple and consist of a single piece that represents both the drying chamber and the solar collector. These dryers can have various shapes depending on the product and the quantity to be dried.

The most common form is that of a solar dryer whose transparent surface is inclined at a well-defined angle depending on the position and generally oriented to the south. The heat is generated by the absorption of solar radiation incident on the product itself, through the transparent surface covering the drying chamber **Figure I.6** [**20**].

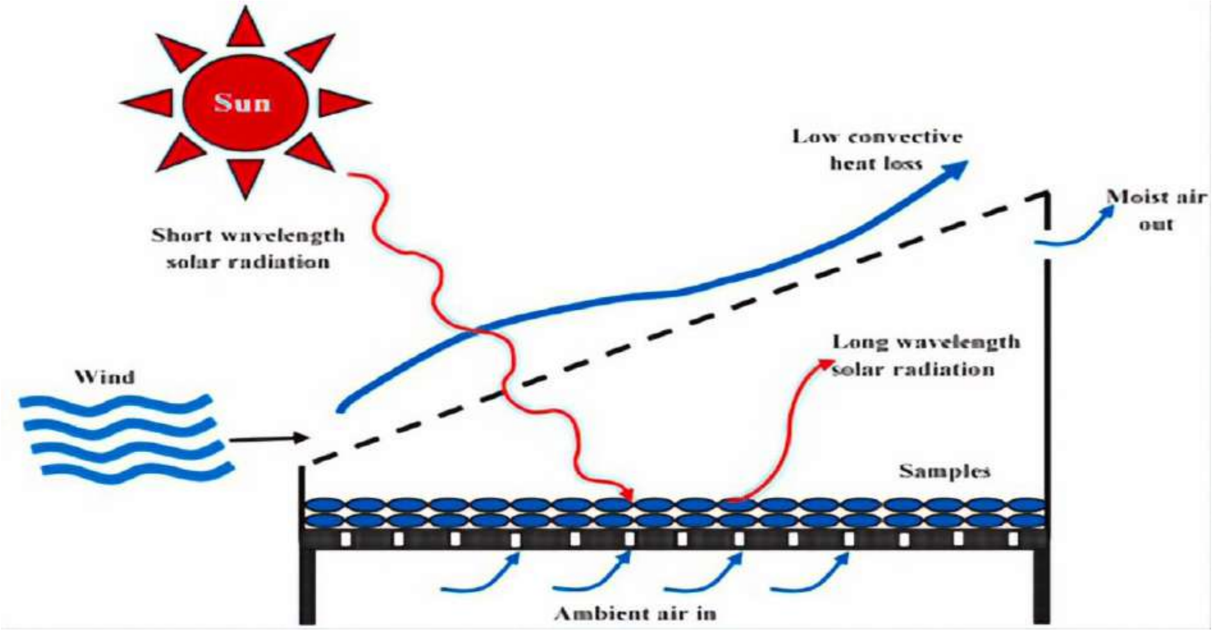


Figure I.6 Direct solar dryer [20]

Table I.2 Advantages and disadvantages of a direct solar dryer[4] :

Advantages	Disadvantages
• Better protection against dust, insects, animals, and rain compared to traditional drying. • No need for skilled labor.	• High temperature at the end of the drying process. • Oxidation of vitamins A and C due to UV rays from the sun. • Low air circulation which limits the speed of drying and increases the risk of mold.

I.10.5 Indirect solar dryers :

In indirect solar dryers, the products to be dried are not directly exposed to solar radiation. They are even shielded from light, leading to better preservation of the nutritional qualities of the food. Indirect dryers essentially consist of two parts: a solar collector and a drying chamber **(Figure I.7)**[**20**]. The solar collector is usually a separate module that is attached to the drying chamber during exposure to the sun, and its inclination is designed to maximize the collection of solar energy. It consists of a glass surface located above and an absorbing surface, usually painted black. The air is first heated in the solar collector, then conducted into the drying chamber where heat transfer from the air to the product and mass transfer from the product to the air occur during the drying air's journey **[4].**

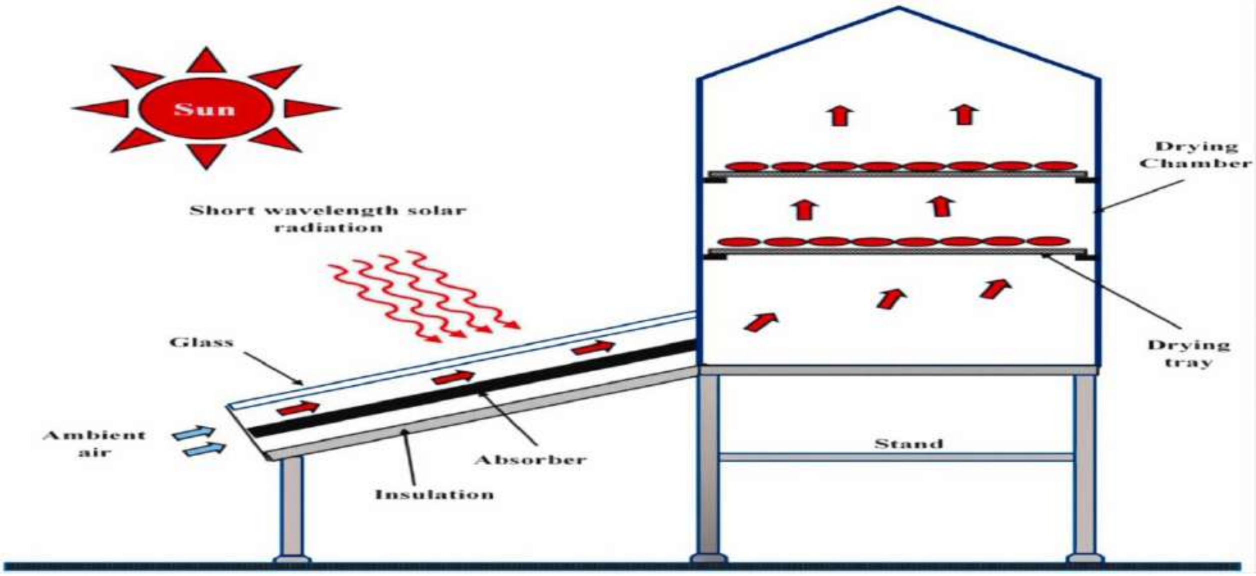


Figure I.7 Direct Solar dryer [20].

Table I.3 Advantages and disadvantages of an indirect solar dryer [4]

Advantages	Disadvantages
• The product is not directly exposed to the sun. It retains its color and nutritional value better (especially vitamins A and C). • Possibility to build this type of dryer locally, with a reduced cost. • Their operation does not require electrical energy or fossil fuels.	• Drying speed is highly variable depending on the climatic conditions and the design of the dryer. • Fragility of the polyethylene materials, which must be replaced regularly.

I.10.6 Hybrid solar dryers :

These dryers use, in addition to solar energy, a supplementary energy source (fuel, electricity, wood, etc.) to ensure a high level of air heating or to provide ventilation. Solar energy is often used in this case to preheat the air. These systems, which are more expensive, are generally reserved for large-scale applications or commercial applications where the quality and flow rate of the final product may depend on the climatic conditions.

The most commonly used drying methods in industry are:

- Hot air drying or "traditional" drying.
- Superheated steam drying.
- Heat pump drying.
- Hot chamber drying.
- Vacuum drying.

The last two drying processes are used especially for wood drying **[21].**

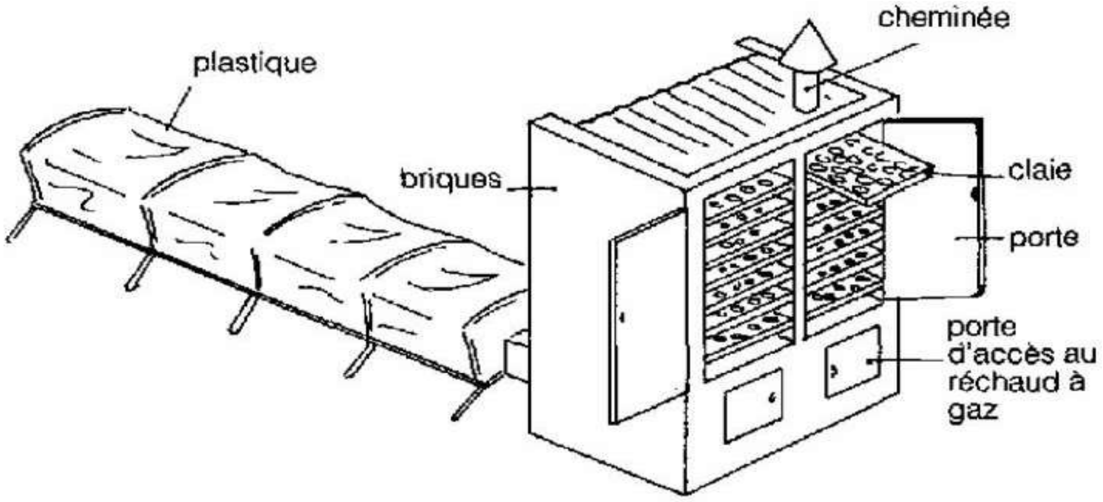


Figure I.8 The principle of a hybrid solar dryer[3].

Table I 4 Table of advantages and disadvantages of a hybrid solar dryer [4]:

Advantages	Disadvantages
• Freedom from weather conditions. • Better control over drying.	• High production and investment costs. • Need for local supply of fuel, electricity, and spare parts.

I.10.7 Mixed Solar Dryer :

Mixed dryers are a combination of direct and indirect dryers. In this type of dryer, the products are subjected to the combined action of direct solar radiation on the product and the heated air from a sensor located below the drying chamber. For mixed dryers, the upper surfaces of the drying chamber and the sensor are covered with glass or transparent films **[4] (Figure I.9) [20].**

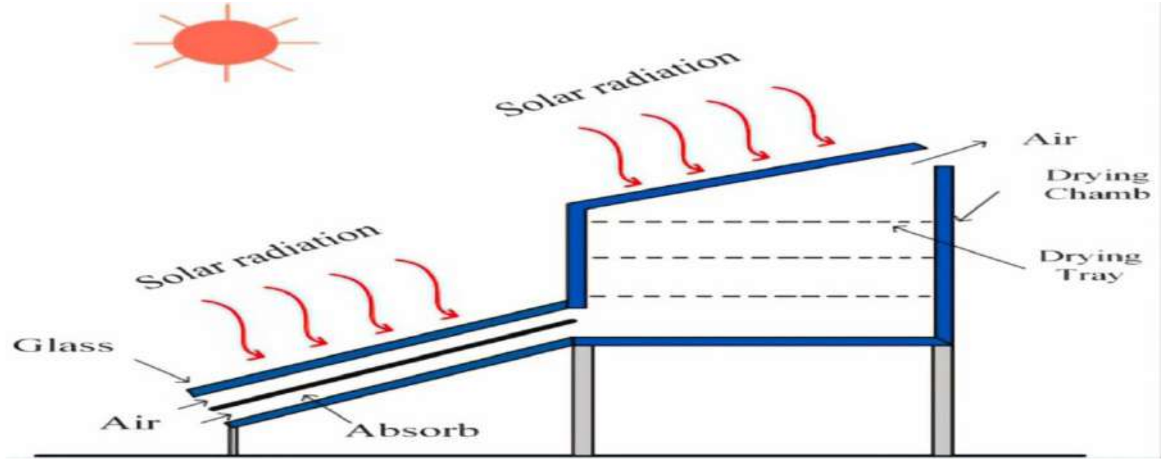


Figure I.9 Mixed solar dryer [20].

I.11 General overview of thermal energy storage :

I.11.1 Storage:

Energy storage involves storing a quantity of energy during a period when it is abundant or less expensive, in a given location, in order to release it later when it is rare or more expensive .

I.11.2 Thermal energy storage:

Thermal energy can be stored in the form of a change in the internal energy of a material in the form of sensible heat, latent heat and thermochemical energy or a combination of these. An overview of the main techniques for storing solar thermal energy is presented in **[16]**

Figure I.10 [16]

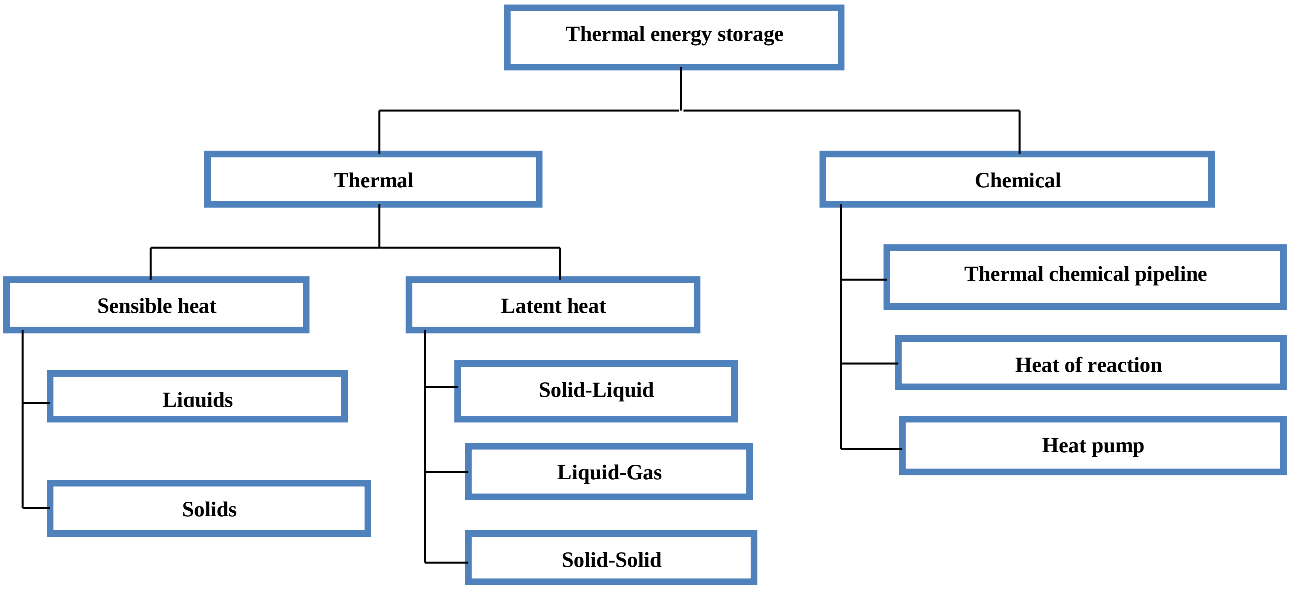


Figure I.10 Different types of thermal storage for solar energy [16].

I.11.2.1 Sensible Heat Storage:

Sensible heat storage is the simplest and most common mode of heat storage. The principle of sensible heat storage is based on increasing the temperature of a material without changing its phase, according to the following law: **[22]**

$$Q = m.C_p.\Delta T \qquad \textbf{(I.1)}$$

Where:

Q: sensible heat [J]

m: mass of the material [kg]

C_p: specific heat capacity of the material [J/kg·K]

ΔT : temperature change [K]

The temperature changes linearly with respect to the stored heat**. [23] (Figure I.11) [24].**

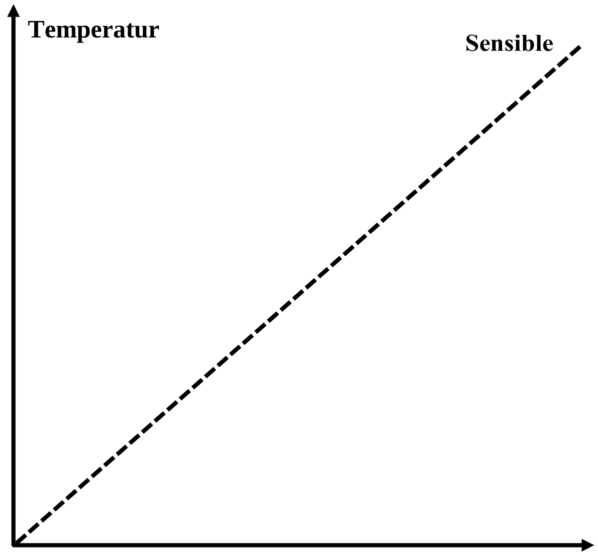


Figure I.11 Temperature increase during sensible heat storage [25].

I.11.2.2 Latent Heat Storage:

Latent heat storage involves heating a material until it changes phase, that is, from solid to liquid, from liquid to gas, or during a solid-solid transition. When the material reaches its phase change temperature, it absorbs a quantity of heat to undergo the transformation, known as the latent heat of fusion or vaporization, depending on the case. Conversely, when the liquid or gas material is cooled, it returns to the solid or liquid phase, releasing its latent heat [25] . The latent heat capacity of a material can be defined as [23] :

$$Q = m.C_p.dT(s) + m.L_f + m.C_p.dT(l) \qquad \textbf{(I.2)}$$

With:

m: mass of the phase change material [kg]

C_p: specific heat capacity of the material [J/kg·K]

L: latent heat of fusion [J/kg]

dT: temperature difference [K]

The equation above describes the sensible heat of the solid phase, the latent heat of fusion, and the sensible heat of the liquid phase. The amount of energy stored can be expressed for the case of solid-liquid transition and is presented on the temperature-energy graph in **Figure I.12 [24]**.

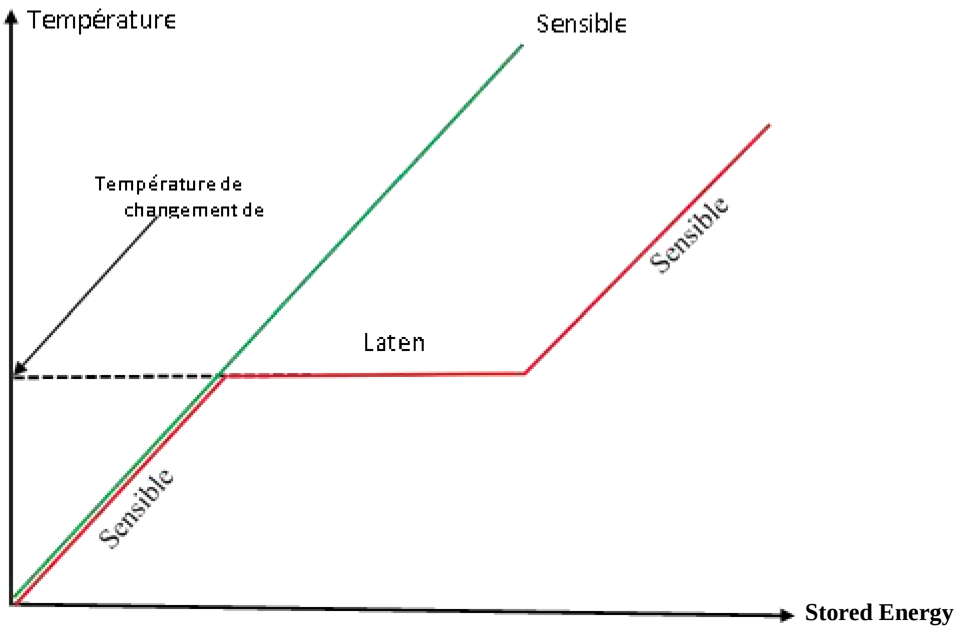


Figure I.12 shows the storage of heat as latent heat for a case of solid-liquid phase change, [23].

I.11.2.3 Thermal-Chemical Storage:

Thermochemical energy is the heat absorbed or released during an endothermic or exothermic chemical reaction. The storage of thermochemical energy is based on the energy of the chemical bonds involved in reversible chemical reactions **[26].**

The stored heat of reaction is often associated with the dissociation of the chemical reactants into two components. All or part of this heat can be recovered later when the synthesis reaction takes place **[25].**

$$A + \Delta H_r \Leftrightarrow B + C \qquad \textbf{(I.3)}$$

Where:

A: Solid or liquid reactant.

ΔH_r: Heat of reaction [J/mol].

B and C: Products in the form of gas, liquid or solid.

Storage by chemical reactions allows for very high energy densities to be achieved.

But these reactions occur at high temperatures, between 300 and 1000 °C, and are generally slow. This technique is still relatively immature at present **[27].**

I.11.3 Comparison of storage systems :

All storage systems are used according to three major steps: charging, storage, and discharging. A large number of storage means can be identified based on their properties, temperature of use, desired storage type, and intended application domain.

To select the type of storage, it will be necessary to look at the intended application. For example, latent and sensible systems will be used more as a buffer storage to smooth out production or defer energy use. On the other hand, thermochimical storage will be more suitable for long-term or seasonal storage that would store excess heat produced by certain installations in the summer to restore it in the winter.

From an economic point of view, the evaluation requires taking into account the investment, operating, maintenance, and recycling costs. These costs often vary depending on the storage volume. Energy density, which is the amount of energy that can be stored per unit of volume, is therefore a critical criterion. For sensible storage, it is the product of the heat capacity, temperature gradient, and density that allows for the calculation of this quantity. To compare materials, a gradient of 100°C has been deliberately used, except for water which cannot be used over a range of 100°C. For latent storage, latent heat is multiplied by density. For thermochimical storage, finally, the reaction heat divided by the molar mass of the product allows for the calculation of energy density **[25] .**

The energy densities obtained as well as the operating temperatures of each thermal storage system are presented for some materials in the following table:

Table I.5 Comparison of different types of storage based on their energy density [29].

Sensible Storage	Temperature (°C)		Heat capacity	Density	Energy density
	Cold	Hot	p (kJ/kg.K)	ρ (kg/m3)	(kWh/m3)
Sand - rock - mineral oil	200	300	1.3	1700	61
Reinforced concrete	200	300	0.85	2200	52
Mineral oil	200	300	2.6	770	56
Water	20	80	4.18	1000	70
Molten salt nitrates	250	350	1.5	1825	76
latent storage	Melting temperature Tm (°C)		Latent heat ΔhS-L(kJ/kg)	Mass density ρ (kg/m3)	Densitéé nergétique (kWht/m^3)
Acide maléique	131-140		235	1590	103
Xylitol	95		232	1500	97
Erythritol	118		340	1450	137
$MgCl_2.6H_2O$	117		165	1569	72
$NaNO_3$	307		172	2260	108
Thermochemical storage	Reaction temperature (°C)		Reaction enthalpy ΔHr (kJ/mol)		Energy density (kWh/m3)
	Charge	Discharge			
$MgH_2+\Delta Hr \leftrightarrow Mg+H_2$	380à1 bar	230 à 4bar	-75		430
$CaCO_3+\Delta Hr \leftrightarrow CaO+CO_2$	700	650	-178		110
$MgH_2+\Delta Hr \leftrightarrow Mg+H_2$	450	25-400	-94.6 (charge) 64.8 (discharge)		300

I.11.4 Phase Change Materials (PCM):

Phase Change Materials (PCMs) are elements that store latent heat during the process of melting and release it during solidification while maintaining a constant temperature. These materials have a high energy storage density and the ability to maintain a constant temperature while absorbing heat during melting and releasing it during solidification. This property has gained interest in the field of thermal management and solar energy systems for buildings and greenhouses.

PCMs melt and solidify over a wide range of temperatures, making them attractive for various applications. Among these materials, paraffin waxes are inexpensive with moderate thermal storage density and low thermal conductivity. Hydrated salts are PCMs with a higher energy storage density and greater thermal conductivity, but they exhibit supercooling and phase segregation [**28**]**.**

I.11.5 Classification of Phase Change Materials (PCMs):

A large number of phase change materials (organic, inorganic, and eutectic) are available in all required temperature ranges. A classification of PCMs is illustrated in **Figure I.13.**

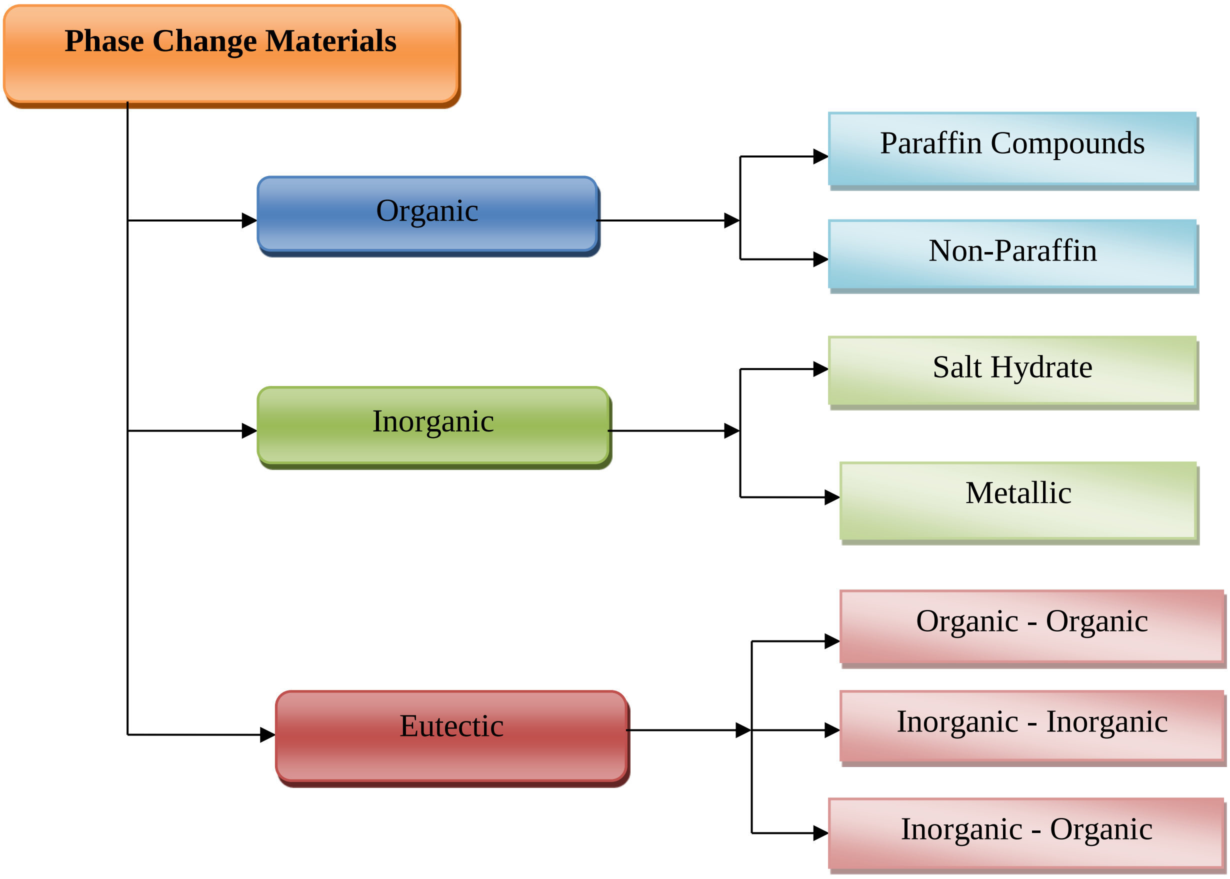


Figure I.13 Classification of Phase change Materials [23].

I.11.5.1 Organic compounds:

Organic compounds mainly include paraffins, sugar alcohols, fatty acids, and other less commonly used compounds such as ketones or esters.

a) Paraffins:

Paraffins are a family of saturated hydrocarbons with the formula C_nH_{2n+2}, with very similar properties. Among solid-liquid PCMs, they are the most commonly used, especially for low-temperature applications (from -10 to 100°C) because they have a latent heat that depends on the molar mass and variable phase change temperatures, giving flexibility to choose the appropriate PCM for each application.

Some examples of paraffins are n-Hexadecane (fusion temperature = 22°C), n-Nonacosane (fusion temperature = 63.4°C), and n-Triacontane (fusion temperature = 65.4°C) [**25**]**.**

b) Non-paraffins:

Non-paraffins are the most abundant phase change materials with very different properties. These organic materials have other subgroups of fatty acids and other non-paraffinic organic compounds such as esters, alcohols, glycols, etc.**[26**]**.**

I.11.5.2 Inorganic compounds:

This group is mainly composed of salts or hydrated salts and metals.

a) Hydrated salts:

The general formula of a hydrated salt is $AB.nH_2O$ (AB = formula of the anhydrous salt, n = number of water molecules). Many hydrated salts have been used as phase change materials. Hydrated salts have a high latent heat of fusion per unit volume and high thermal conductivity. Additionally, their volume during the transition phase is low. They are not very corrosive and are compatible with plastics. The most commonly used hydrated salt is $CaCl_2.6H_2O$ **[29].**

I.11.5.3 Eutectic mixtures:

Eutectic mixtures are substances composed of several pure components. Generally, they are mixtures of organic and inorganic components (organic-organic, organic-inorganic, inorganic-inorganic). They have two main advantages; they have a net melting point similar to a pure substance, and their volumetric latent heats are slightly higher than those of pure organic compounds. Their two main disadvantages are that there is little available data on the thermal properties of these materials, and they are not widely used in industrial systems [**30**] **.**

I.11.6 Properties of phase change materials (PCM):

PCMs can only be used as heat storage materials when their thermodynamic, kinetic, and chemical properties meet certain criteria.

Table I.6 Properties of phase change materials (PCM)

Thermodynamic criteria [31]:	• Melting temperature within the appropriate temperature range for the desired application. • High latent heat per unit mass. • High specific heat. • Congruent melting. • Low volume change during the phase transition.
Kinetic criteria [26]:	• No significant supercooling, ensuring heat release at the same temperature as the storage temperature. • Adequate crystallization rate for efficient power exchange with the heat transfer fluid.
Chemical criteria [27]:	• Chemical stability. • No chemical decomposition, ensuring viability of latent heat storage system. • No corrosive action on construction materials or containers. • Non-harmful, non-flammable, and non-explosive nature.
Economic criteria:	• Availability and abundance of the material. • Cost-effectiveness. • Low cost.

I.12 Conclusion :

In conclusion, choosing the best drying technique, consider the specific product needs, energy efficiency, cost-effectiveness, and product quality. Efficient energy management and utilization can be achieved through thermal storage, especially by using phase change materials (PCM). When selecting a thermal storage system, take into account the intended use, energy density, and economic factors.

Chapter II :

Literature review

II.1 Introduction:

A literature review on direct solar dryers involves a comprehensive examination of this technology's history, designs, and applications. It delves into the various configurations and advancements made in the field, exploring the range of materials that can be effectively dried using solar energy. By analyzing the advantages and limitations of solar dryers, such as their energy efficiency, cost-effectiveness, and environmental impact, this review will provide a valuable insight for those seeking to enhance and optimize solar drying technologies, including us.

II.2.Direct solar dryer literature review:

A direct solar dryer is a device that uses solar energy to dry agricultural products, food, and other materials. The solar dryer typically consists of a collector, a storage unit, and a drying chamber. The collector captures solar radiation and converts it into heat, which is stored in the storage unit. The heated air is then passed through the drying chamber, where it removes moisture from the material being dried. The most important research on this topic

[Dissa A.O et al, 2011.] The study aimed to determine the direct solar drying characteristics of two types of mangoes, Amelie and Brooks. A solar dryer with four trays was used under the weather conditions of the fruit harvest period, and direct solar drying curves were established. Ten mathematical models were used to fit the curves, and a direct solar drying model was used to simulate the drying process. The study found that it took at least four days to reach the range of preservation water contents, and the drying curves depended on the variety. The "two-term" and "Approximation of diffusion" models were suitably fitted to the drying curves, with an R2 of 0.9888, RMSE of 0.0283, E of 9.1283%, and c2 of 1.3314 × 10^4. The drying rates and efficiency significantly decreased with the number of drying days, ranging between 0 and 0.15 g kg^-1 s^-1 and between 0 and 34%, respectively. The diffusivity weakly varied with variety and strongly decreased with the number of drying days. The study also found that the direct solar drying model suitably simulated the drying kinetics, with Amelie having an R2 of 0.989 and E of 7.623%, while Brooks had an R2 of 0.9924 and E of 4.961%. The final water content was about 24.83% for Amelie and 66.32% for Brooks. The study concludes that Amelie is the most suitable variety for direct solar drying [**31**].

[Abu Tefera et al, 2013.] The study evaluated the performance of two models of direct solar potato dryers - wooden box dryer and pyramid shape dryer - and compared them to open sun drying methods. The study found that both dryers offered benefits like protection against contaminants, dust, and insects, resulting in better quality products. The pyramid dryer was found to be better in creating a more conducive drying environment and is also cheaper and easier to manufacture in rural areas.[**31**]

Figure II.1 Box solar dryer [31]

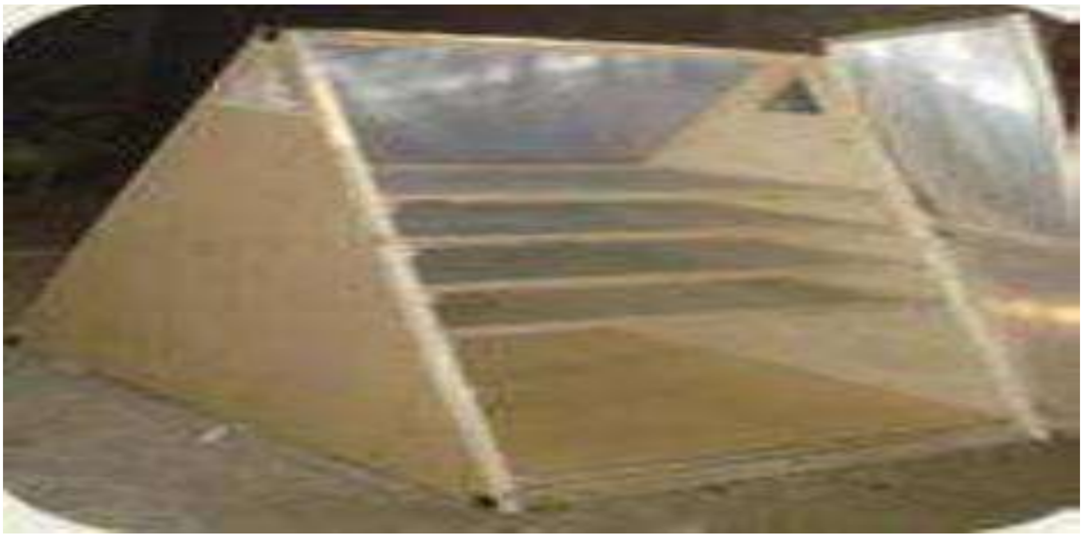


Figure II. 2 Pyramid shape solar dryer [31]

[Letícia Ferraresi Hidalgo et al ,2021.] In this research, a direct solar dryer assisted by photovoltaic module was developed, and its performance was evaluated under natural and forced air convection experiments for drying of green onion. The photovoltaic module provided electrical power to eight coolers that allowed the renewal of air inside the equipment, making the dryer capable of operating independently of electrical energy distribution grid. The researchers monitored moisture and colorimetric parameters during the drying process of green onion and analyzed the drying kinetics They found that both natural and forced convection experiments showed a constant rate period followed by a falling rate peri The effective diffusivity values were determined for both operating conditions. The average efficiencies of the solar dryer and the specific energy consumption were also calculated for each condition. Little color variation was observed between fresh and dried green onions, which is important for maintaining the quality of the material.[**32**]

Figure II.3 Direct solar dryer [32]

Figure II.4 Green onion fresh leaves and the stalks that were discarded [32]

[S. Nabnean et al ,2020.] In this study, a direct forced convection household solar dryer was built with a polycarbonate plate cover on a parabolic-shaped flat plate collector. The dryer was used to dry bananas. Five batches of 10 kg bananas were dried in the solar dryer between January and July 2019. The researchers monitored the drying air temperature in the dryer and observed a range of 35 ◦C to 60 ◦C from 8:00 a.m. to 6:00 p.m. They also measured the moisture content of the bananas and found that it decreased from 72% (wb) initially to 28% (wb) within 4 days. In comparison, the moisture content of sun-dried samples reached 40% (wb) in the same time period. The solar dryer significantly reduced drying time by 48% compared to natural sun drying. The solar-dried bananas were of high quality in terms of flavor, color, and texture. The researchers estimated the payback period of the dryer to be around 1.1 years.[**33**]

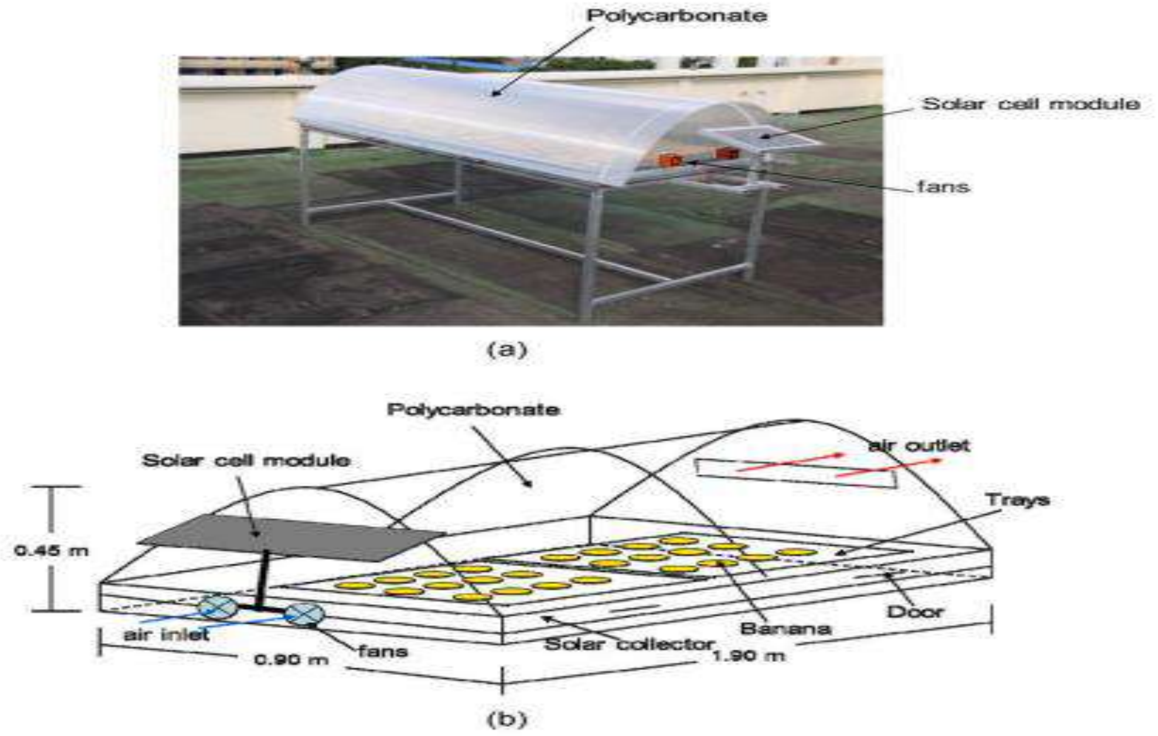


Figure II.5 Pictorial view of the solar dryer (a) and schematic diagram of the solar dryer system (b). [33]

[Y.I. Sallam et al ,2013.] In this work, the authors investigated the effect of flow mode and type of solar dryer on the drying kinetics of whole mint. They used two identical prototype solar dryers, one direct and one indirect, each with six perforated galvanized steel trays loaded with 1.2 kg of fresh whole mint. The prototypes were operated under natural and forced convection modes, with the latter using a fan mounted in the exit channel to achieve an air velocity of 4.2 m/s at the entrance channel. The drying behavior was monitored over two days, with data manually recorded every 2 hours from 10 a.m. to 6 p.m. The authors also fitted ten empirical models to the drying curves to analyze the drying rate and effective diffusivity coefficient of the mint [**34**].

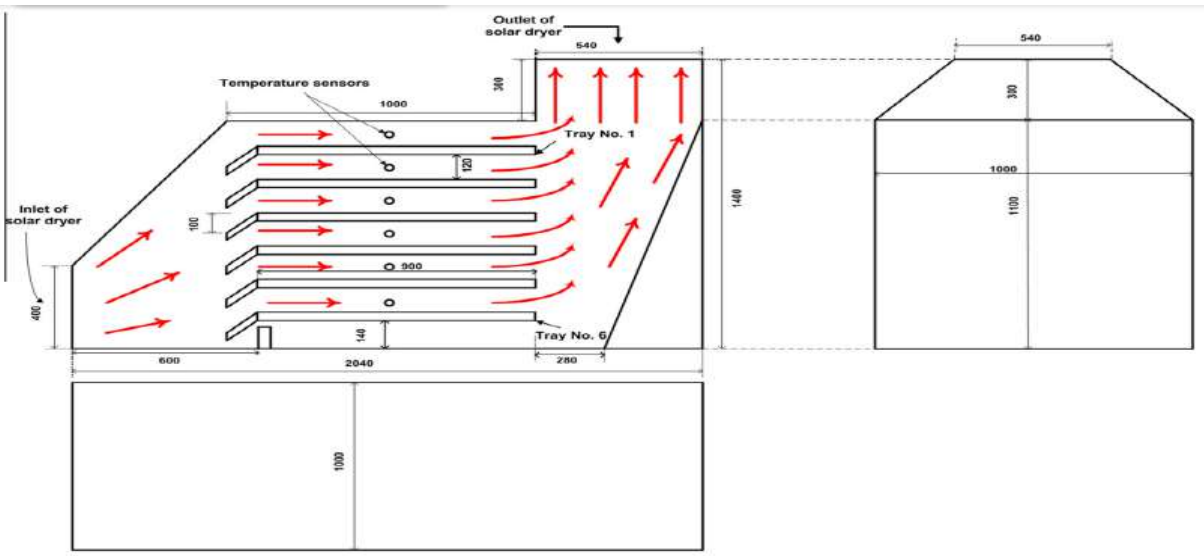


Figure II.6 schema of the solar dryer (dimensions in mm – the bold arrows refer to air streamlines). [34]

Figure II.7 Photograph of the direct solar dryer. [34]

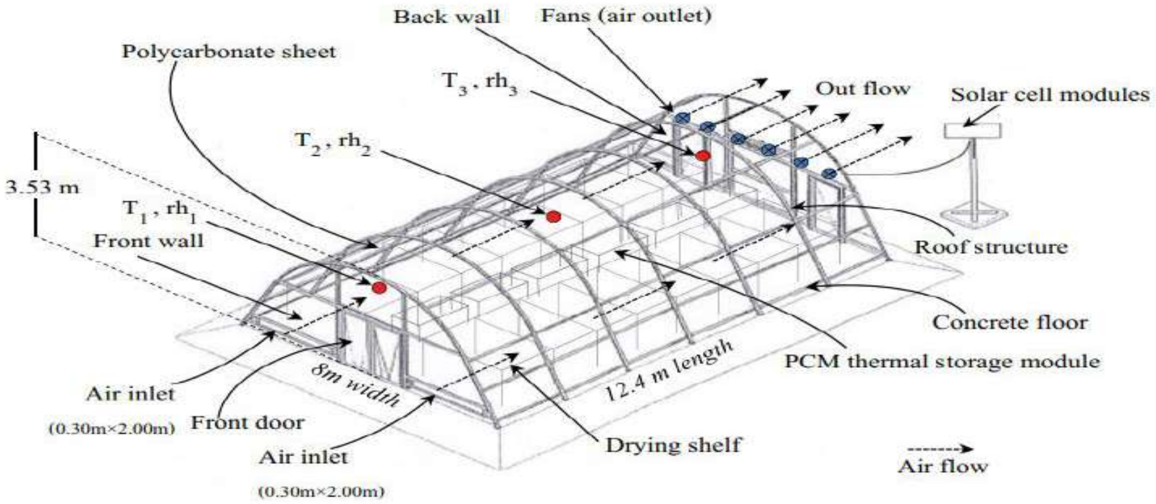
II.3. Phase change material (PCM) in direct solar dryers:

Thermal storage can also be used in solar dryers to improve their efficiency and increase their ability to dry food and agricultural products. Solar dryers are devices that use solar energy to dry crops, fruits, vegetables, and other agricultural products, but they can be limited in their effectiveness due to fluctuations in solar radiation and ambient temperatures.

To overcome these limitations, Phase change material (PCM) can be incorporated into the design of solar dryers. This is typically achieved by using a thermal mass, such as rocks or bricks, as a heat sink to store thermal energy during periods of high solar radiation and release it later when the solar radiation is low. This can help to maintain a consistent temperature and humidity level inside the dryer, which is important for preserving the quality of the products being dried. We present to you some of these works

[P. Pankaew et al ,2020.] Alarge-scale study was conducted on the performance of a solar dryer of the greenhouse type integrated with a phase change thermal storage system for drying chili. Experimental studies were carried out to compare the performance of this dryer with that of another large-scale greenhouse solar dryer without PCM thermal storage and sun drying. The chili, with an initial moisture content of 74.7% (w.b), was dried to a final moisture content of 10.0% (w.b) in 2.5 days, 3.5 days and 11 days using the solar dryer integrated with PCM thermal storage, the solar dryer without PCM thermal storage and sun drying, respectively [**35**].

Figure II.8 Large scale solar dryer for polycarbonate greenhouse. [35]



(Ti = temperature atposition i, i = 1, 2, and 3 rhi = relative humidity at position i, i = 1, 2, and 3). (The drying room is the space enclosed by the roof structure, front wall, back wall andconcrete floor.)

Figure II.9 Structure of the large-scale greenhouse solar dryer integrated with PCM thermal storage system and the positions of the measurements. [35]

[Zaineb Azaizia et al ,2019.] A new solar dryer integrated with a mixed solar greenhouse with PCM storage unit has been studied for its performance. The experimental results show that the air temperature inside the solar greenhouse with PCM is about 7.5 °C higher than other dryers during the night. The relative humidity in the drying chamber with PCM is about 18.6% lower than the ambient relative humidity after sunset. The water content has an effective reduction of 95% in 30 hours for a dryer with PCM, whereas it took 55 hours in a dryer without PCM and 75 hours in full sunlight [**36**]

Figure II.10 Experimental solar greenhouse drying system. [36]

[N. Vigneshkumar et al,2021 .] The researchers conducted a study comparing the drying of sliced potatoes in two types of solar dryers: one without PCM (Plain Dryer) and one with PCM (PCM Dryer). The air flow rate was consistent at 0.065 kg/s, and the dryers operated from 10.00 a.m. to 7.00 p.m. The results indicated that the presence of PCM in the solar collector extended the elevated drying room temperature for an additional two hours beyond the solar period. Additionally, the use of paraffin as PCM increased the moisture removal from potato slices by 5.1% per day [**37**].

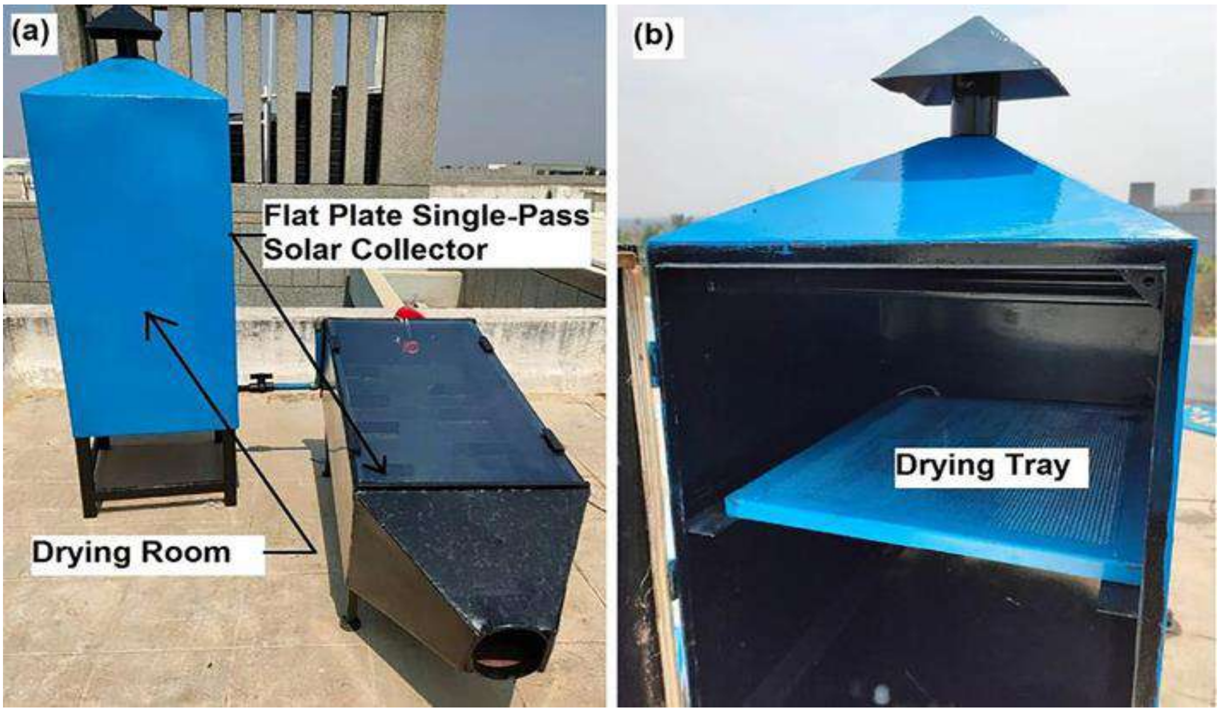
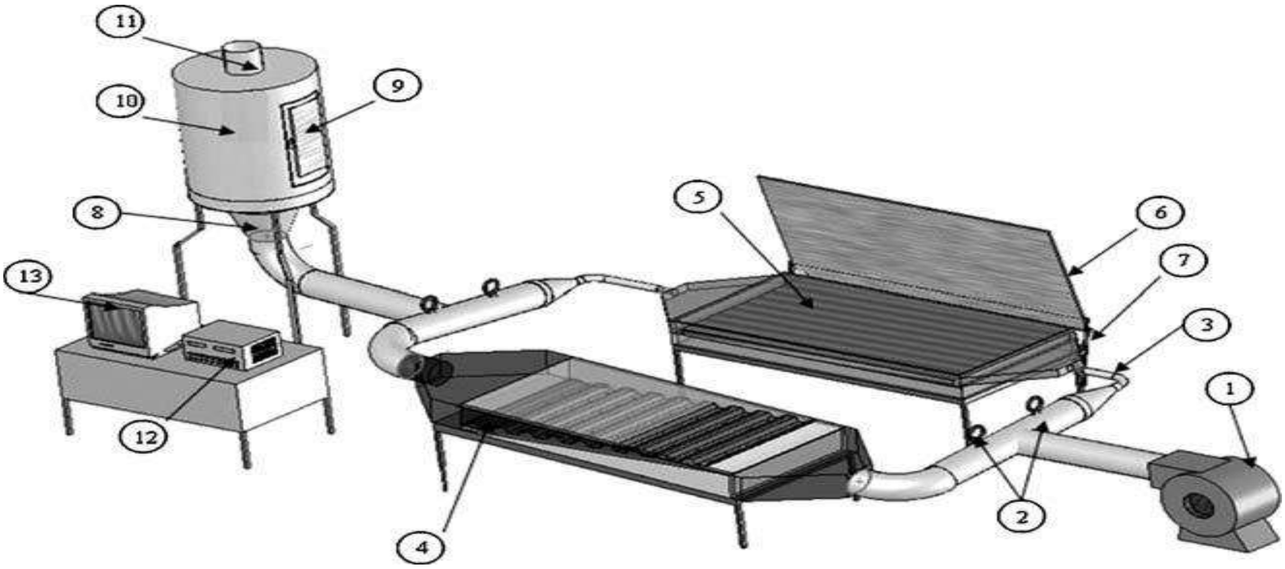


Figure II.11 Experimented solar dryer (a) Complete set-up (b) Inside drying room. [37]

[Gülsah Cakma et al ,2010.] In this study, a new type of dryer was developed to investigate the drying kinetics of seeded grapes. The dryer system consisted of an expanded-surface solar air collector, a solar air collector with phase-change material (PCM), and a drying room with swirl elements. The expanded-surface solar air collector facilitated efficient heat transfer and turbulence, while the solar air collector with PCM allowed drying to continue even after sunset. The swirl elements in the drying room created a swirling airflow. The results indicated that the proposed novel dryer system showed promise in achieving lower moisture levels and shorter drying times for the grapes [**38**].



(1) Fan, (2) valves, (3) connection pipe, (4)expanded-surface solar air collector, (5) collector with PCM،(6) adjustable mirror, (7) adjustable collector tripod, (8)diffuser, (9) observation glass, (10) drying room, (11) air exitchimney, (12) datalogger and (13) PCM.

Figure II.12 Schematic view of manufactured experimental set-up [38].

II.4.Heat recovery in direct solar dryer:

Thermal recovery in a direct solar dryer refers to the process of capturing and reusing the heat energy generated by the sun to help dry agricultural products or other materials.

Thermal recovery can be achieved in a few different ways. One common method is to use a heat exchanger or thermal storage system, which captures the excess heat generated by the sun and stores it for later use. This stored heat can then be used to continue drying the materials during periods when there is little or no sunlight. Another method of thermal recovery is to use a heat recycling system, which captures the hot air that is generated during the drying process and recirculates it back into the drying chamber. This helps to maintain a consistent temperature and reduce the amount of energy needed to continue drying the materials. Here are some of the works that researchers have dealt with on this topic

[N.I. Roman-Roldan et al ,2021 .] This study investigated the use of an air recirculation system to improve air flow distribution, velocity, and temperature in a mixed greenhouse dryer for solar drying. Using numerical simulations with 3D CFD ANSYS FLUENT code, the researchers considered six different locations of axial fans and additional elements such as a false ceiling and internal walls to analyze their contribution. They found that installing an air recirculation system can significantly increase air velocity and temperature, resulting in reduced drying time and a more homogeneous moisture content in dry products. Specifically, the air velocity increased from 0.71 m/s to 1.5 m/s, and the temperature increased from 315 K to 360 K, representing an increase of approximately 111.26% and 11.11%, respectively, compared with the greenhouse without an air recirculation system [**39**].

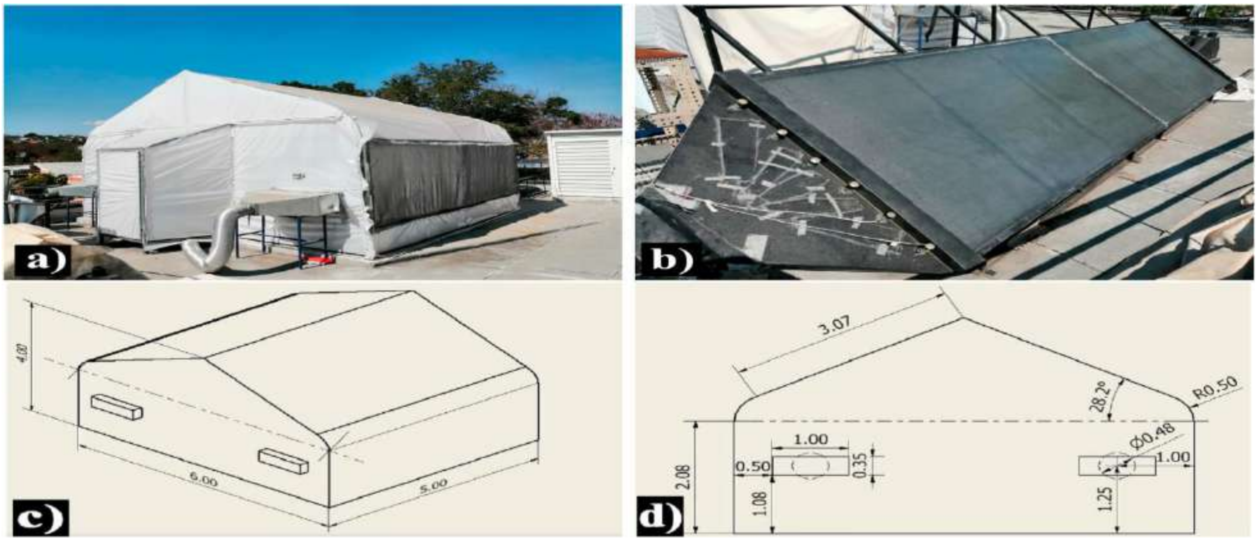


Figure II.13 Solar drying system, a) Greenhouse; b) Solar collectors; c) General dimensions; d) Specific dimensions [39]

[Roonak Daghigh et al ,2016] This study focused on the development and testing of a heat-pipe evacuated tube solar dryer equipped with a heat recovery system. The system utilized water as the working fluid in the solar loop and air as the intermediate fluid in the drying section. The heat recovery system was implemented to enhance overall system efficiency and optimize solar energy utilization. By transferring heat from the solar loop to the blown air via a heat exchanger, the heated air was directed to the main chamber of the dryer where the drying products were placed. The researchers conducted tests in the weather conditions of Sanandaj city and observed the effectiveness of the heat recovery system. They achieved a maximum outlet air temperature of approximately 44.3°C with a volumetric flow rate of 0.0328 m3/s. The exergetic efficiency of the system was determined to be around 11.7% by the end of the day [**40**].

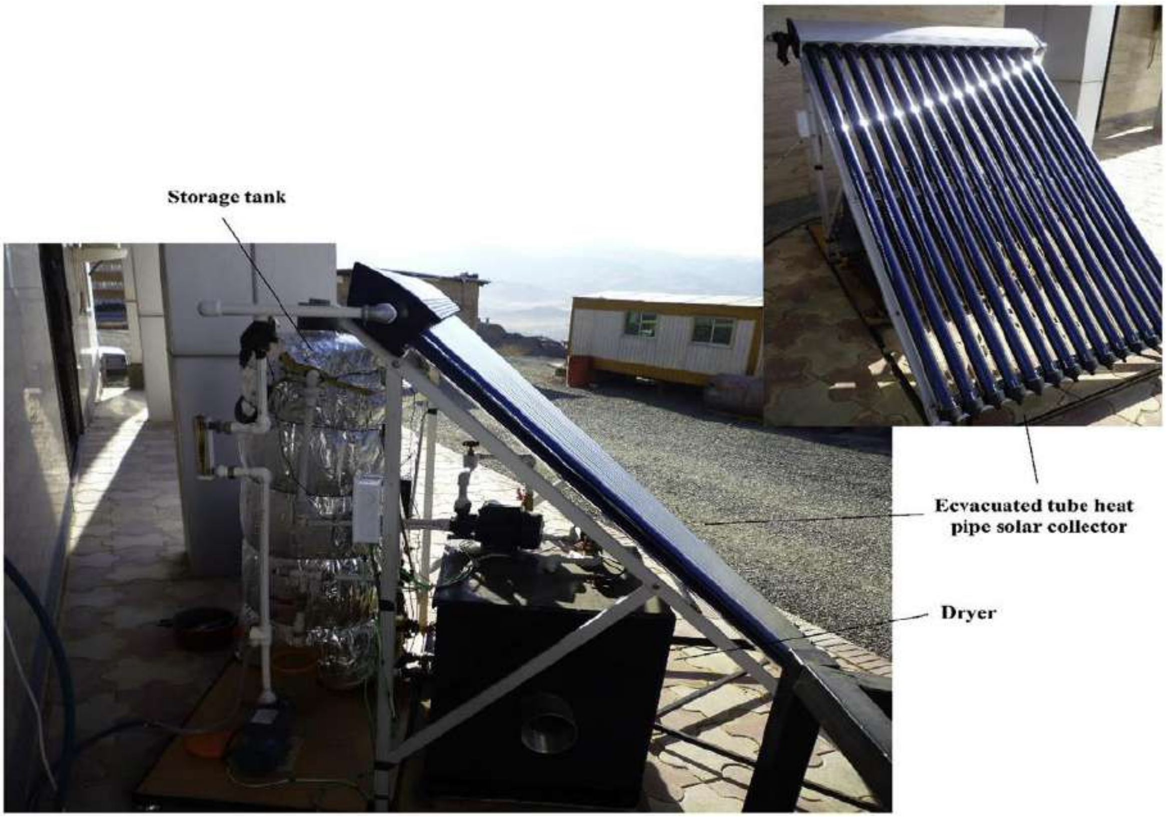


Figure II.14 Overall view of the manufactured device. [40]

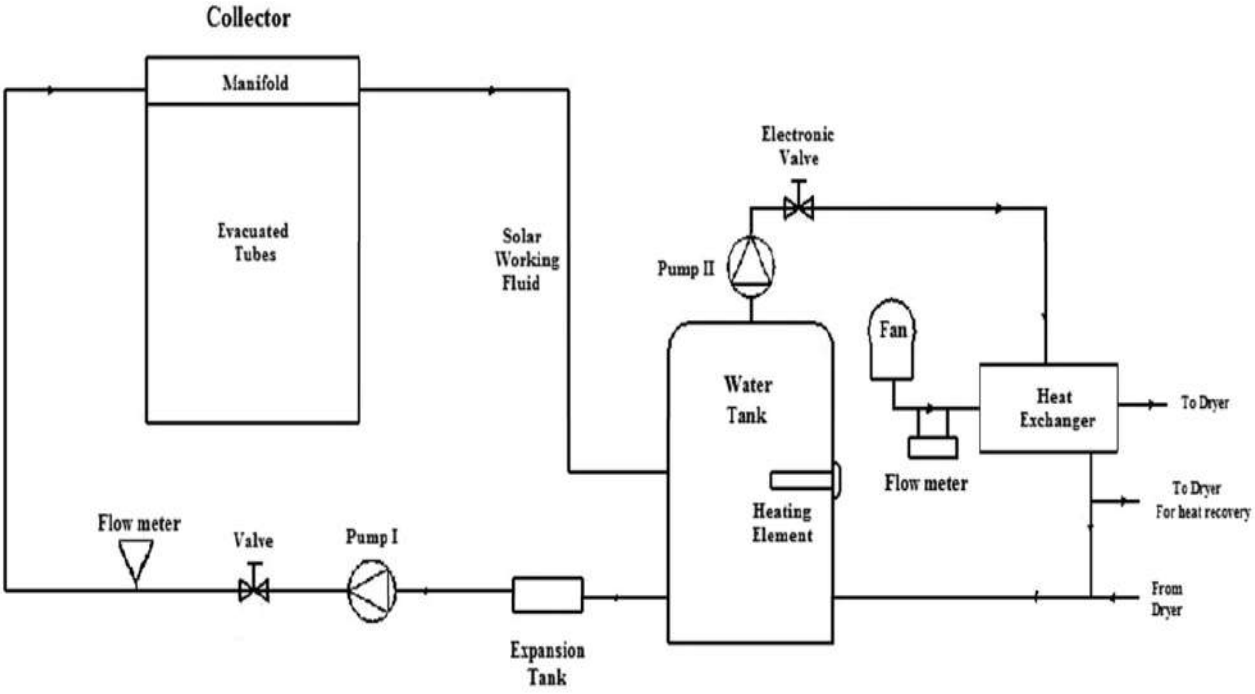


Figure II.15 Schematic of system. [40]

[Mustafa Aktas et al, 2016.] The study aimed to improve the efficiency of drying melon slices by using a solar-heat recovery assisted infrared dryer. The researchers added a solar air collector and heat recovery unit to reduce energy consumption. The experiments showed that the heat recovery unit provided a significant portion of the total energy input and the solar air collector had an efficiency of 50.6%. The study demonstrated the successful combination of solar and infrared energy with heat recovery in food processing [**41**]

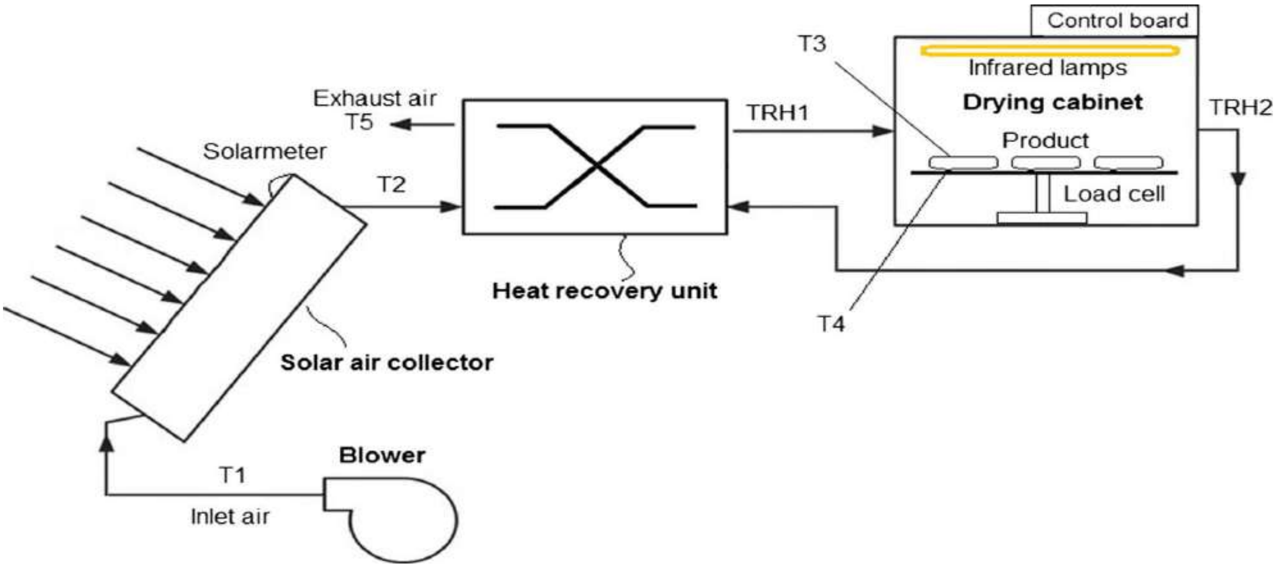


Figure II.16 Solar-heat recovery assisted infrared dryer (SHRAIRD) [41] .

[Saman Zohrabia et al ,2019.] This study focused on investigating the impact of exhaust air recirculation on the exergetic performance of a pilot-scale convective dryer used for drying poplar wood chips. The researchers varied parameters such as drying air temperature, air volume flow rate, and exhaust air recycle fraction, and assessed the exergetic efficiencies of the drying system and chamber. The findings demonstrated that exhaust air recirculation significantly improved the overall functional exergetic efficiency of the drying system, although it led to a substantial increase in drying time at a 100% recycle fraction **[42]**.

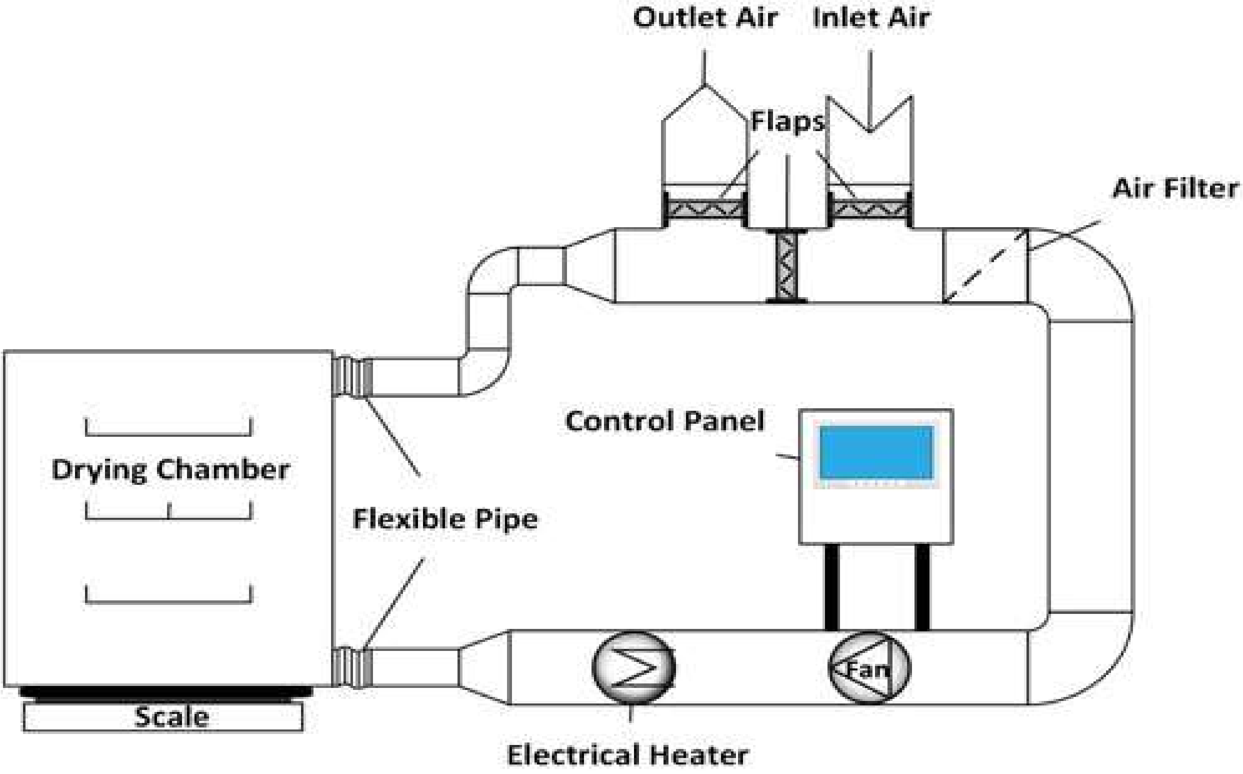


Figure II .17 Schematic of the developed pilot-scale batch dryer. [42]

[Thanwit Naemsai el al , 2019.] The study found that the solar-assisted heat pump dryer with heat recovery was able to recover considerable thermal energy from the exhausted air. Specifically, the dryer system was able to achieve a coefficient of performance (COP) of approximately 3.17, which indicates the amount of useful energy delivered by the dryer per unit of energy consumed. Additionally, the specific energy consumption of the dryer system was approximately 2.21 kWh/kg, which is significantly lower than that of a traditional drying method.

These results demonstrate the potential for a solar-assisted heat pump dryer with heat recovery to significantly reduce the amount of thermal energy required for the drying process **[43]**.

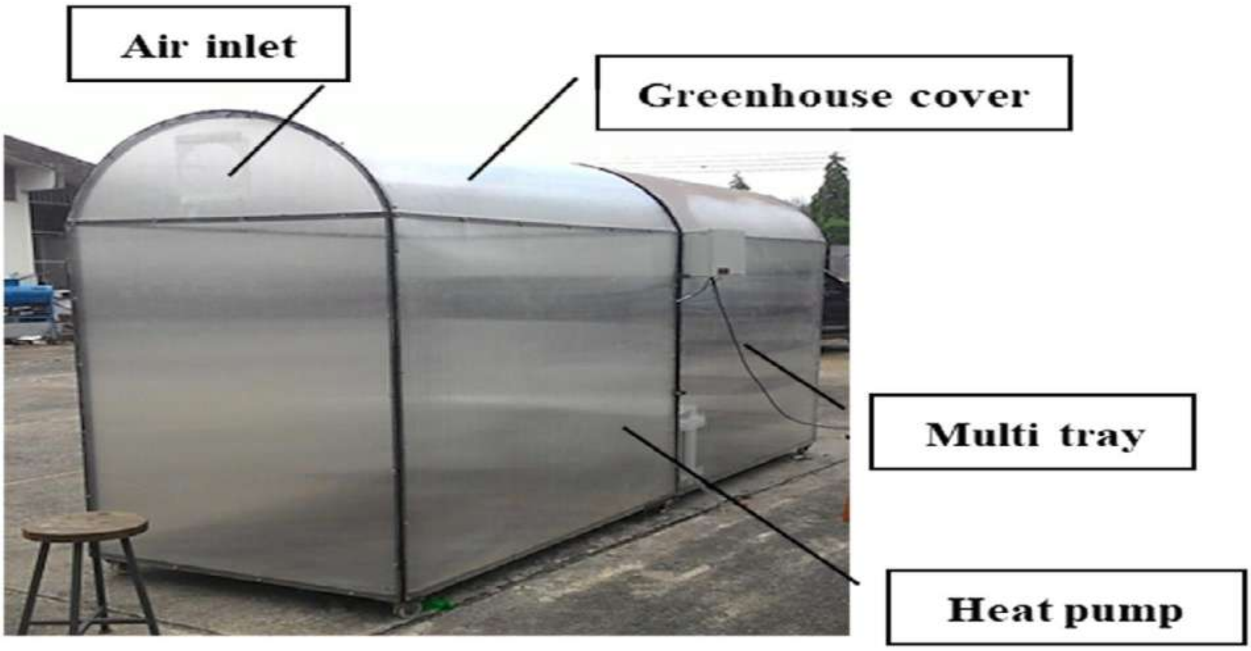


Figure II. 18 **Experimental setup of the solar-assisted heat pump dryer. [43]**

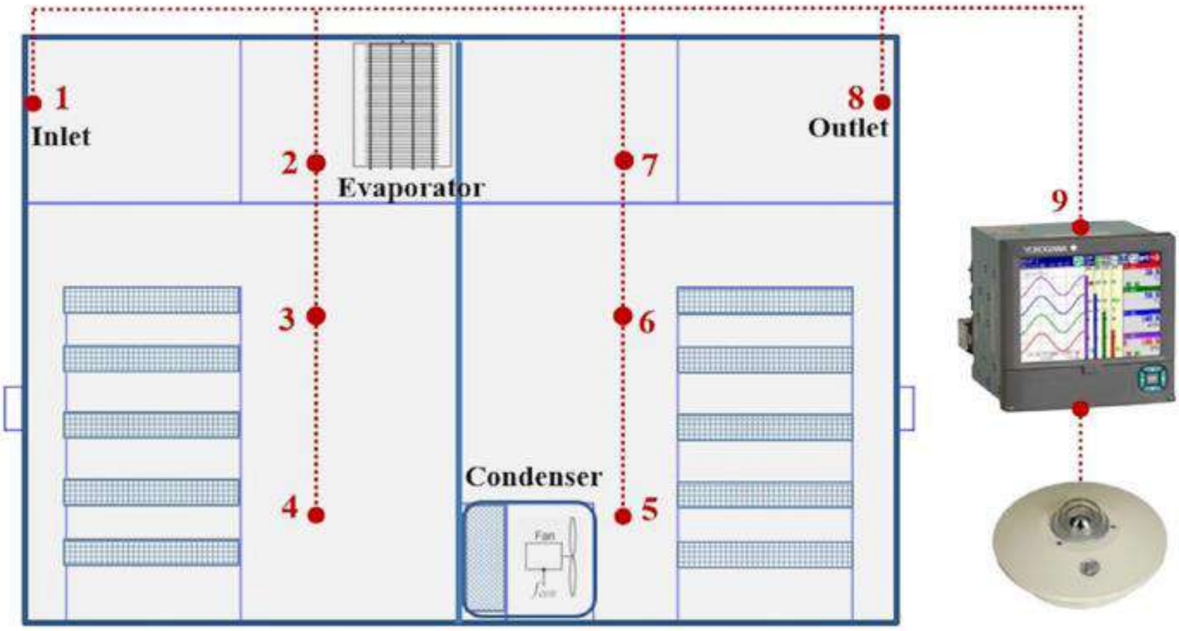


Figure II.19 Experimental apparatus for drying performance. [43]

II.5.Conclusion:

After conducting a thorough bibliographical study on the subject, we have concluded that direct sun drying is a complex and extensive research area with both theoretical and practical aspects. As a result, we have decided to conduct an experimental and mathematical investigation into the impact of various technics of enhancements on the efficiency and effectiveness of direct solar dryers. In the upcoming chapter, you will find a detailed description of the experimental setup, methods, and materials utilized.

Chapter III :

Materials and Methods

Chapter IV :

Results And Discussions

General Conclusion And Outlook

GENRERAL CONCLUSION AND OUTLOOK:

In this dissertation, we have conducted an extensive investigation into the direct solar dryer with thermal energy storage equipped with a heat recycling system, aiming to explore its viability, advantages, and limitations as a sustainable and efficient solution for drying applications. Through a comprehensive analysis and evaluation of the technology, several key findings have emerged, shedding light on its potential impact and future prospects.

Two preliminary models of direct solar dryers were tested, one of which was equipped with a heat recovery system to recirculate the used air back into the dryer, while the other did not have this system. The tests were conducted under real weather conditions in the Ghardaia region to assess the impact of any modifications made. Under the same weather conditions, the average air temperature inside the solar dryers equipped with the heat recovery system reached 55 degrees Celsius, with the average absorber plate temperature at 66 degrees Celsius. On the other hand, the average air temperature inside the solar dryer without the heat recovery system reached 62 degrees Celsius, with the average absorber plate temperature at 75 degrees Celsius.

The performance of the two preliminary prototypes of direct solar dryers was evaluated by drying peppers, the initial moisture content was reduced from 93% to 11% in three to four days.

The dryer equipped with the heat recovery system demonstrated faster drying rate with a decrese of drying time up to one day, and a gain of temperature up to 20 degrees (approximately 30%) compared to the dryer without heat recovery.

Ten mathematical models were used to describe the drying kinetics of the thin layer of peppers. The results indicated that the Logarithmic and Midilli-Kucuk models were the most suitable for describing the solar drying process of the product in the tested preliminary models .

Due to the high temperature inside the dryer equipped with the heat recovery system, it was suggested to incorporate phase change material (PCM) containers to store excess heat within the direct solar dryer system to enhance its performance. This would allow capturing and storing the extra heat during periods of strong sunlight, enabling the continuation of drying processes even under low solar radiation or absence of sunlight.

It should be noted that the observed weather conditions during the testing period were extremely unfavorable, making it difficult to detect expected temperature changes or heat transfer. However, the study was limited in conducting further tests due to time constraints imposed on the research project.

In conclusion, the direct solar dryer with heat storage and heat recovery system represents a promising and sustainable approach for drying applications. Therefore, the development of drying techniques is much more crucial than merely considering the design or modeling aspects. In other words, this study deserves to continue exploring other horizons.

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