



**UNIVERCITE KASDI MERBAH OUARGLA**

**Faculty of Renewable Energies**

**Department of Hydrocarbons, Renewable Energy,**

**and Earth and Universe Sciences**



## **Thesis**

**Submitted in partial fulfillment of the requirements for the degree of**

## **MASTER**

**Specialty: Mechanical Engineering**

**Option: Renewable Energies in Mechanics**

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**Thesis Title:**

**Optimal Design and Performance Analysis of Hybrid  
Solar PVT Dryers Integrated with Phase Change  
Materials for Agri-Food Preservation**

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Academic Year: 2024/2025

# *Thanks*

First and foremost, we thank God Almighty for granting us the strength, health, and perseverance to undertake and complete this work.

We extend our deepest gratitude to Prof. **Dr. Ayache Khirreddine** and **Dr. Ben Touila Omar** for their unwavering guidance, invaluable advice, and constant support throughout this journey. Their expertise and encouragement have been instrumental in shaping this work, and we sincerely appreciate their dedication.

We are also profoundly grateful to **Dr. Hadjadj Abdessami**, Professor at the University of Kasdi Merbah Ouargla, for his meticulous review of our manuscripts and for graciously accepting to chair the evaluation committee. His insights and feedback have been immensely beneficial.

Lastly, we would like to express our sincere appreciation to all our professors for their generosity, patience, and unwavering support, despite their demanding academic and professional responsibilities.

**HIDER IBRAHIM & HAMADOU BRAHIM**

## الإهداء

لم تكن الرحلة قصيرة، ولم يكن من المفترض أن تكون كذلك. كان الحلم بعيداً، والطريق لم يكن مفروشاً بالتسهيلات، لكنني تمكنت من الوصول.

أهدي تخرجي إلى من كان اسمه يرافقني بفخر، إلى من أزال الأشواك من طريقي، مهذاً الطريق للعلم، إلى "والدي العزيز" الذي رحل عن عالمنا. بعد فضل الله، كل ما حققته هو بفضل والدي، الرجل الذي لم يحصل على جزء بسيط مما حققناه، والذي سعى طوال حياته ليكون أفضل منا. أدعو الله أن يتغمده بواسع رحمته ويسكنه فسيح جناته.

إلى اليد الخفية التي أزلت الأشواك من طريقي، وإلى من تحمل كل لحظة ألم مررت بها ودعمتني في ضعفي ومرحني، "أمي الحبيبة"، أنت ملاكي في الحياة، تجسدين الحب والحنان، وأنت معنى وجودي. كانت دعواتك سر نجاحي.

إلى من ساهموا بشكل كبير في تشجيعي وتحفيزي، ومن تعلمت منهم الصبر والاجتهاد، وخاصةً إلى "إخوتي وأخواتي".

وخصوصاً إلى شيماء وذكري، اللتين أضفتما إلى تجربتي لحظات من الفرح والإنجاز. فلكما مني كل الشكر والتقدير.

إلى "أصدقائي" ورفقاء السنين، وإلى كل من قدم لي المساعدة والدعم في هذه الرحلة، أنا ممتن لكم جميعاً. ما كنت لأصل إلى ما أنا عليه اليوم لولا طبيبتكم ودعمكم، بعد مشيئة الله.

وأخيراً، نسأل الله التوفيق في حياتنا جميعاً.

## الإهداء

بإسم الله والصلاة والسلام على رسول الله الحمد لله رب العالمين، الذي بنعمته تتم الصالحات، وبتوفيقه تكتمل الخطى. له الشكر أولاً وآخرًا، ظاهرًا وباطنًا، فما كان لهذا العمل أن يتم لولا عونه وتيسيره.

إلى عائلتي الغالية، نور حياتي وسندي الأکید، فحبهم الصادق وإرشادهم الحكيم تشكّلت مسيرتي واكتمل إنجازي. إلى والدي الحبيب، يا من غرس فيّ قيم المثابرة والتفاني، وعلمني أن العظمة تكمن في إتقان العمل، في كل حرف في هذا البحث يحمل بصمة توجيهاتك الثمينة. إلى أمي العزيزة، يا من سهرت لياليك لتضيئي لي طريق العلم، هذا الجهد القليل هو عربون شكرٍ لعطائك الذي لا ينضب، أتمنى أن أكون كما حلمت بي. إلى إخوتي وأخواتي، زينة حياتي وفرحة قلبي، شكرًا لكونكم دائمًا حائط الصدّ الذي أرتكز عليه، ولصبركم على غيابي أثناء إنجاز هذا العمل. إلى رفاق الدرب والأصدقاء الأعزاء، الذين كانوا خير معين في رحلة البحث، فبمساندتكم وملاحظاتكم القيمة اكتملت هذه الصورة. وخصيصًا، إلى شيماء وذكرى، رفيقتي في الأعمال التطبيقية، فلكما مني كل التقدير. كما لا يفوتني أن أخصّ بالشكر إخوتي الأعزاء من الغرف الجامعية C64 عامة، وبالأخص منير، وعماد، وأبوبكر، وأيوب، الذين كانوا لي نعم الإخوة والسند في كل خطوة لما قدموه من دعم ومؤازرة. وإلى الأستاذ الدكتور حجاج عبد السميع المؤطر الكريم الذي كان سندًا وداعمًا لنا في كل خطوة خطوناها، بفضل توجيهاته السديدة وصبره الكبير، كان لهذا العمل أن يسير بثبات ويكتمل على أفضل وجه. كل الشكر والتقدير والامتنان لشخصه الكريم. وختامًا، إلى كل من مدّ لي يد العون ولو بكلمة تشجيع، أقول لكم من الأعماق جزاكم الله خيرًا، فما كان لهذا العمل أن يرى النور لولا دعمكم الكريم.

## ملاخص

تبحث هذه الأطروحة في أداء أربع نماذج أولية لمجففات شمسية تعمل بالحمل الحراري الطبيعي والقسري، وقد قسمت النماذج إلى نموذجين بالحمل الطبيعي ونموذجين بالحمل القسري حيث كان النموذج الأول مجفف شمسي يعمل بالحمل الحراري الطبيعي والنموذج الثاني مجفف شمسي يعمل بالحمل الحراري القسري أما النموذج الثالث فهو مجفف شمسي يعمل بالحمل الحراري الطبيعي ومزود بنظام استرداد الحرارة والأخير مجفف شمسي بالحمل الحراري القسري مزود بنظام استرداد الحرارة. تهدف الدراسة إلى تعزيز كفاءة المجففات الشمسية من خلال معالجة مشكلة نقص الطاقة الشمسية خلال فترات زمنية محددة. وللتغلب على هذه المشكلة، تم دمج نظام استرداد الحرارة لتقليل فقدان الحرارة، حيث زُوِّدَت المجففات بصناديق من شمع البارافين (PCM) لتخزين الطاقة الحرارية، مما يُتيح تجفيفاً فعالاً حتى في ظل ظروف الطاقة الشمسية المنخفضة. أُجريت اختبارات تجريبية فيمخبر الطاقات الجديدة والمتجددة في المناطق الصحراوية والجافة بكلية علوم المادة ومخبر هندسة الطرائق بمركز البحث العلمي بالقطب الجامعي 3، جامعة قاصدي مرباح بورقلة، في ظل ظروف جوية حقيقية. خضع النموذجين الأولين لاختبارات بالحمل الطبيعي، حيث وصلت درجة حرارة الهواء الداخلي إلى 90.1 درجة مئوية في المجفف الشمسي المزود بنظام استرداد الحرارة، و73.8 درجة مئوية في المجفف الشمسي غير المزود بهذا النظام. سُجِّلت درجات حرارة الامتصاص المتوسطة عند 69.2 درجة مئوية في المجفف المزود بنظام استرداد الحرارة، و62.5 درجة مئوية في المجفف غير المزود به. تم إجراء تقييم أداء مجففات الحمل الحراري الطبيعية في البيوت الزجاجية باستخدام الليمون كمنتج للتجفيف. استُخدمت عشرة نماذج رياضية لوصف حركية تجفيف الطبقة الرقيقة من الليمون. كما خضع النموذجين الثانيين لاختبارات بالحمل الحراري القسري، حيث تم الوصول إلى درجة حرارة الهواء الداخلي إلى 103.1 درجة مئوية في المجفف الشمسي المزود بنظام استرداد الحرارة، و84.8 درجة مئوية في المجفف غير المزود بهذا النظام. كما سُجِّلت درجات حرارة الامتصاص المتوسطة عند 90.1 درجة مئوية في المجفف المزود بنظام استرداد الحرارة، و79.6 درجة مئوية في المجفف غير المزود به. انخفض محتوى الرطوبة في الليمون من 94% إلى 10% خلال فترة تتراوح بين ثمانية وتسعة ساعات. أدى استخدام المجفف المزود بنظام استرداد الحرارة إلى تجفيف أسرع لمدة تصل إلى ست ساعات، مع زيادة في درجة حرارة التجفيف بنحو 20 درجة. حُدِّدَت كفاءة النماذج الأولية عند 40% للمجفف المزود بنظام استرداد الحرارة، و30.76% للمجفف غير المزود به. بشكل عام، تُظهر هذه الدراسة إمكانية دمج أنظمة استرداد الحرارة وتخزين الطاقة الحرارية في المجففات الشمسية لتحسين أدائها خلال فترات انخفاض توافر الطاقة الشمسية. تُقدم النتائج رؤى قيّمة لتحسين تصميم وتشغيل المجففات الشمسية في الصوب الزراعية، بما يضمن تجفيفاً فعالاً للمنتجات الزراعية مع تقليل استهلاك الطاقة.

## **Résumé**

Cette thèse examine la performance de quatre prototypes de séchoirs solaires fonctionnant par convection naturelle et forcée. Les dispositifs sont répartis comme suit : deux modèles à convection naturelle et deux à convection forcée. Le premier modèle est un séchoir solaire à convection naturelle, tandis que le second utilise une convection forcée. Le troisième intègre un système de récupération de chaleur avec convection naturelle, et le quatrième combine convection forcée et récupération de chaleur. L'objectif de l'étude est d'améliorer l'efficacité des séchoirs solaires en répondant au problème de l'insuffisance de l'énergie solaire à certaines périodes. Pour y remédier, un système de récupération de chaleur a été intégré, associé à des boîtes de stockage à base de paraffine (PCM) afin d'optimiser l'accumulation thermique et de permettre un séchage efficace même en conditions solaires réduites. Les essais expérimentaux ont été réalisés dans des conditions climatiques réelles au sein du Laboratoire des Énergies Nouvelles et Renouvelables en Zones Arides et Sahariennes (LENRZAS) et au Laboratoire de Génie des Procédés (LGP) du Centre de Recherche Scientifique, Université Kasdi Merbah - Ouargla. Pour les modèles à convection naturelle, la température de l'air intérieur a atteint 90,1 °C dans le système avec récupération de chaleur, contre 73,8 °C sans ce système. La température moyenne d'absorption était de 69,2 °C avec récupération et 62,5 °C sans. Le citron a été utilisé comme produit à sécher, et dix modèles mathématiques ont été appliqués pour modéliser la cinétique de séchage en couche mince. Concernant les modèles à convection forcée, les températures maximales de l'air intérieur enregistrées étaient de 103,1 °C (avec récupération) et 84,8 °C (sans récupération), avec des températures d'absorption moyennes de 90,1 °C et 79,6 °C respectivement. La teneur en humidité du citron a diminué de 94 % à 10 % en 8 à 9 heures. L'intégration du système de récupération a permis de réduire le temps de séchage à environ 6 heures et d'augmenter la température de séchage d'environ 20 °C. Le rendement thermique a été évalué à 40 % pour le modèle avec récupération, contre 30,76 % sans. Globalement, cette recherche met en évidence le potentiel de l'intégration des systèmes de récupération de chaleur et de stockage thermique dans les séchoirs solaires afin d'en améliorer les performances, notamment dans les serres agricoles et sous faible ensoleillement.

## **Abstract**

This thesis investigates the performance of four prototype solar dryers operating under both natural and forced convection modes. The systems are classified into two natural convection models and two forced convection models. The first is a solar dryer based on natural convection, the second utilizes forced convection, while the third and fourth incorporate a heat recovery system under natural and forced convection, respectively. The study aims to enhance the efficiency of solar dryers by addressing the challenge of limited solar energy availability during specific periods. To mitigate this, a heat recovery system was integrated, along with paraffin wax (PCM) thermal storage units, to minimize heat losses and enable effective drying even under low solar irradiance conditions. Experimental testing was conducted under real atmospheric conditions at the Laboratory of New and Renewable Energies in Arid and Saharan Areas and the Laboratory of Process Engineering at the Scientific Research Center, Kasdi Merbah University, Ouargla. Under natural convection, the maximum internal air temperature reached 90.1 °C for the dryer equipped with heat recovery, compared to 73.8 °C for the conventional system. The average absorber temperature was 69.2 °C with heat recovery and 62.5 °C without. Lemon slices were used as the drying product, and ten mathematical models were employed to describe thin-layer drying kinetics. For forced convection models, the internal air temperature reached 103.1 °C with the heat recovery system, and 84.8 °C without. The average absorber temperatures were 90.1 °C and 79.6 °C, respectively. Moisture content in lemon decreased from 94% to 10% within 8 to 9 hours. The heat recovery system enabled faster drying (up to 6 hours) and increased drying temperature by approximately 20 °C. Thermal efficiency was found to be 40% for the system with heat recovery and 30.76% for the one without. Overall, the study demonstrates the potential of integrating heat recovery and thermal storage systems into solar dryers to improve their performance, particularly for greenhouse agricultural applications and in periods of limited solar availability.

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# Nomenclature

## Latin-alphabet

Symbol	Definition	Unit
m	Mass	Kg
Cp	Specific Heat	J·kg <sup>-1</sup> ·k <sup>-1</sup>
T	Temperature	K
Lf	Latent Heat of Fusion of MCP	J·kg <sup>-1</sup>
Q	Sensible Heat	kg·s <sup>-1</sup>
ṁ	Mass Flow Rate	kg·s <sup>-1</sup>
MR	Reduced Moisture Content	Kg of water/Kg of dry matter
MR <sub>o</sub>	Initial Moisture Content	Kg of water/Kg of dry matter
MR <sub>eq</sub>	Equilibrium Moisture Content	Kg of water/Kg of dry matter
MR <sub>pred</sub>	Predicted Moisture Content	Kg of water/Kg of dry matter
MR <sub>exp</sub>	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 <sub>v</sub>	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

### Greek Alphabet

Symbol	Definition
$\Delta$	Variation
$\eta$	Thermal efficiency
$\tau_c$	Cover transmissivity
$\chi^2$	Minimum reduced chi-square

### Indices

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

# **General Introduction**

### GENERAL INTRODUCTION

The rising of global demand for energy is largely driven by economic growth and the expanding energy needs of countries. Research indicates that the global energy supply doubles approximately every 20 years. However, this surge in energy consumption has led to serious environmental issues, primarily due to the continued reliance on fossil fuels. As fossil fuel resources decline driven by increased usage for electricity generation, heating, refrigeration, and air conditioning attention has shifted towards renewable energy sources such as solar, wind, ocean, and geothermal energy. Despite their promise, the use of renewable energy remains significantly lower compared to fossil fuels [1].

Recently, there has been growing momentum toward adopting renewable energy, particularly solar energy, due to its direct availability, sustainability, safety, cost-efficiency, and environmental benefits. Solar energy has been historically used for a variety of applications, including the drying of clothes, fish, and agricultural products.

Drying processes, however, are notably energy-intensive, as they require significant thermal energy to evaporate the moisture contained within products. A range of energy sources(including LPG, coal, biomass, and solar energy)are utilized to meet these thermal demands. Among them, solar energy stands out as the most widely used renewable source in drying applications, with a long history of use by humanity.

Traditional outdoor sun drying remains the most common and cost-effective method of solar drying. Nonetheless, it suffers from several critical limitations: extended drying times, exposure to contamination (dust, insects, animals), lack of control over the process, degradation of product quality (loss of color, nutrients), vulnerability to adverse weather, the need for large drying areas, and high labor demands.

To overcome these challenges, solar dryers have been developed. These systems dry products in enclosed environments or insulated cabinets at controlled temperatures, offering a more efficient and hygienic alternative to open-air drying. Compared to open sun drying under similar solar radiation, solar dryers provide higher temperatures and lower relative humidity levels, creating a more suitable drying environment(especially for agricultural goods)within a typical temperature range of 45 °C to 60 °C.However, a major limitation of solar dryers remains the intermittent and unpredictable nature of solar radiation, which affects their reliability and restricts widespread adoption. To mitigate these issues, auxiliary heat sources such as electric

heaters, LPG burners, and biomass stoves are often integrated into solar dryers. Additionally, thermal energy storage systems are used to store excess heat for use during cloudy conditions or at night. Two main types of thermal energy storage are employed in solar dryers: Sensible Heat Storage (SHS): stores thermal energy by raising the temperature of storage materials like water, rocks, sand, or concrete. Latent Heat Storage (LHS): uses phase change materials (PCMs), such as paraffin wax or calcium chloride hexahydrate, which store and release energy during their solid-liquid phase transitions. LHS systems are gaining attention due to their high energy storage capacity, ability to release heat at a nearly constant temperature, and compact design. While several designs of direct-type solar dryers such as tunnel and trapezoidal configurations have been investigated, there is a gap in the literature regarding the integration of a direct-type solar dryer with both a PCM-based thermal storage unit and a novel heat recovery system.

The main objective of this study is to conduct experimental and mathematical investigations on a newly designed direct solar dryer that integrates paraffin wax as a phase change material for thermal energy storage, alongside an innovative heat recovery system. The experimental work is carried out at the Faculty of Materials Science, Kasdi Merbah University of Ouargla, located at a latitude of  $32.37^\circ$  North and a longitude of  $3.77^\circ$  West.

Study Specific Objectives:

- To design and develop a new direct-type solar dryer incorporating a phase change thermal storage system and an innovative heat recovery unit;
- To experimentally evaluate the performance of the developed solar dryer prototypes using parameters such as internal drying temperature and moisture content of the product;
- To compare the performance of various modified solar dryer prototypes and assess the impact of design improvements.

The findings of this research could serve as a reference point for future studies on the adaptation of hybrid solar dryers. The **first chapter** is devoted to the literature review, where we examine scientific works related to the concepts discussed. The **second chapter** focuses on the methodological approach adopted in this study and highlights the design of the storage system integrated into the indirect solar dryer prototype, as well as the evaluation conducted. **Chapter three** presents the results of the experimentation.

# Overview of Solar Dryers and Phase Change Materials (PCM)

## **I Overview of Solar Dryers and Phase Change Materials (PCM)**

### **I.1 Introduction**

It has long been acknowledged that solar drying is a conventional and economical way to preserve agricultural goods. However, there are a number of serious disadvantages to traditional open-air sun drying, such as exposure to UV rays, dust contamination, and the influence of outside elements including insects, animals, and microbes. Meeting international quality and sanitary requirements is frequently hampered by these restrictions. Sun drying is a common practice, but it takes a long time and has a significant chance of developing mold, especially in bad weather. Additionally, it necessitates a lot of work and exposes the items to environmental pollution. More sophisticated solar drying systems have been created in response to these difficulties. Direct, indirect, and mixed-mode solar dryers are among them. Additionally, depending on the airflow system, solar dryers can be Solar dryers can also be classified according to whether they use forced or natural convection as their airflow technique. In order to improve drying performance and dependability[1][2].This chapter offers an introduction of sun drying systems, their classifications, and the use of Phase Change Materials (PCM) as an energy storage solution .

### **I.2 Definition of Drying:**

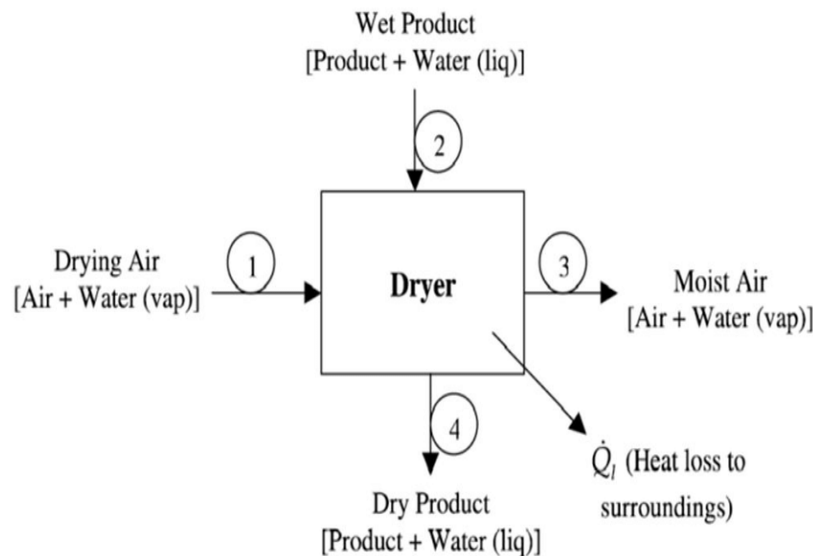
Drying is a very important process applied to both agricultural and industrial products. It is the process of removing moisture from products. Drying reduces bacterial growth in products, making it useful for preserving them for a long time. Drying is either a preservation method or a step in the transformation of certain products. It is used both in rural areas for drying agricultural products, and meats, and in the industrial world, such as in the food industry, textiles, etc. Biologists have observed that by reducing the moisture content of food to between 10 and 20%, bacteria, fungi, and enzymes are almost entirely neutralized. The flavor and most of the nutritional value are preserved and concentrated. Dried products can be stored for several months. Additionally, a dried product weighs about 1/6 of the fresh food product. They do not require special equipment for storage and are easy to transport [3].

### **I.3 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 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

- Heat transfer to provide the latent heat required for vaporization;
- The movement of water or water vapor through the wet product to extract it from the products [4] .



**Figure I.1:** Schematic Drying Mechanism [4]

#### I.4 Solar Dryers

There is a wide variety of dryers, and depending on the perspective taken, they can be classified in different ways. One possible criterion is the texture of the product, which influences how it is handled and how it comes into contact with drying air or heated surfaces. Another classification can be based on the drying principle itself. For instance, in boiling dryers, the product is heated to a temperature where the vapor pressure of its moisture equals the ambient total pressure. In convective dryers, the product is placed in an airflow with a vapor pressure lower than that at the product's surface. Solar dryers are typically divided into three categories:

- Direct solar dryers, where products are exposed directly to sunlight.
- Indirect solar dryers, where products are not in direct contact with sunlight.
- Mixed solar dryers, which combine both methods.

The drying rate is a key factor when choosing the appropriate drying method. In solar drying, relative humidity significantly influences the process. Other important design decisions include

the type of absorber, construction materials, the angle of inclination, and the transparent cover oriented toward the sun [5].

#### **I.4.1 Importance of solar dryer**

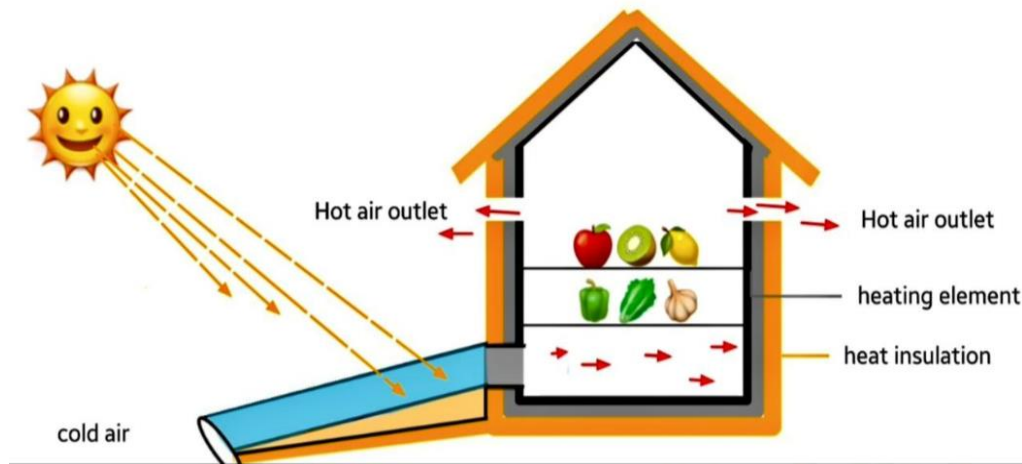
Drying is one of the important post handling processes of agricultural production. It has been applied since time immemorial to preserve agricultural products. It is known as the process of removing moisture from a product and can be implemented [6]. It is considered a crucial technique in the preservation of agricultural products, especially in regions with abundant sunlight. It offers a sustainable and eco-friendly alternative to conventional drying methods that often rely on fossil fuels. By utilizing solar energy, solar dryers reduce post-harvest losses, improve product quality, and enhance shelf life by effectively removing moisture, which inhibits microbial growth. Additionally, solar drying minimizes contamination from dust, insects, and environmental pollutants, ensuring better hygiene compared to open sun drying. From an economic perspective, solar drying lowers energy costs and increases the income of farmers and small scale producers by enabling value addition and market expansion [7].

#### **I.4.2 Working Principle of Solar Dryers**

Solar dryers utilize solar energy to remove moisture from products, primarily food items, through controlled heating and airflow. This method offers a hygienic and efficient alternative to traditional sun drying. Solar dryers operate by converting sunlight into heat energy, which is then used to evaporate moisture from the products. The basic components include:

- **Solar Collector:** Captures solar radiation and converts it into heat. The collector typically consists of a black surface to absorb sunlight efficiently.
- **Drying Chamber:** An enclosed space where products are placed for drying. Heated air from the solar collector is directed into this chamber.
- **Airflow System:** Facilitates the movement of hot air through the drying chamber, carrying away moisture evaporated from the products.

By increasing the temperature of the air, its relative humidity decreases, enhancing its capacity to absorb moisture from the products. This process continues until the desired moisture content is achieved.[8]



**Figure I.2:** Principle of operation of solar dryer

### I.4.3 Main factor of solar dryer

Solar drying systems are generally classified into two types: direct and indirect. They can also be categorized as either active or passive. The efficiency of food drying in these systems is primarily influenced by three interrelated factors: temperature, air flow rate, and humidity. Although there is variation in opinions regarding optimal drying temperatures, most studies agree on a range between 35°C and 82°C, with 43.5°C to 60°C being the most commonly used [4]

#### A. Solar Radiation Intensity

The amount of solar energy available directly influences the drying rate. Higher solar radiation leads to increased temperatures within the dryer, enhancing moisture evaporation from the product. However, fluctuations due to weather conditions can affect consistency.

#### B. Drying Air Temperature

Elevated air temperatures accelerate the drying process by increasing the vapor pressure difference between the product's moisture and the surrounding air. Optimal drying temperatures typically range between 35.5°C and 70°C, depending on the product being dried.[9]

#### C. Airflow Rate and Velocity

Adequate airflow removes the moist air from the drying chamber, maintaining a gradient that favors continuous moisture loss from the product. Air velocities between 1–2 m/s are often recommended to ensure efficient drying without causing physical damage to delicate products.[9, 10]

**D. Relative Humidity of Drying Air**

Lower relative humidity in the drying air enhances its capacity to absorb moisture from the product. High ambient humidity can slow down the drying process, making it essential to design dryers that can preheat or dehumidify incoming air in humid climates.[10, 11]

**E. Initial Moisture Content of the Product**

Products with higher initial moisture content require longer drying times and more energy. Understanding the moisture characteristics of the specific product is crucial for designing an effective drying process.

**F. Dryer Design and Type**

The configuration of the solar dryer—be it direct, indirect, or mixed-mode—affects drying efficiency. Indirect dryers, for instance, can offer more controlled drying conditions, protecting products from direct sunlight and potential contamination.[9]

**G. Geographical and Climatic Conditions**

Local climate, including average temperatures, humidity levels, and solar insolation, plays a significant role in solar drying performance. Regions with high solar insolation and low humidity are ideal for solar drying applications.

**I.4.4 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.[2]

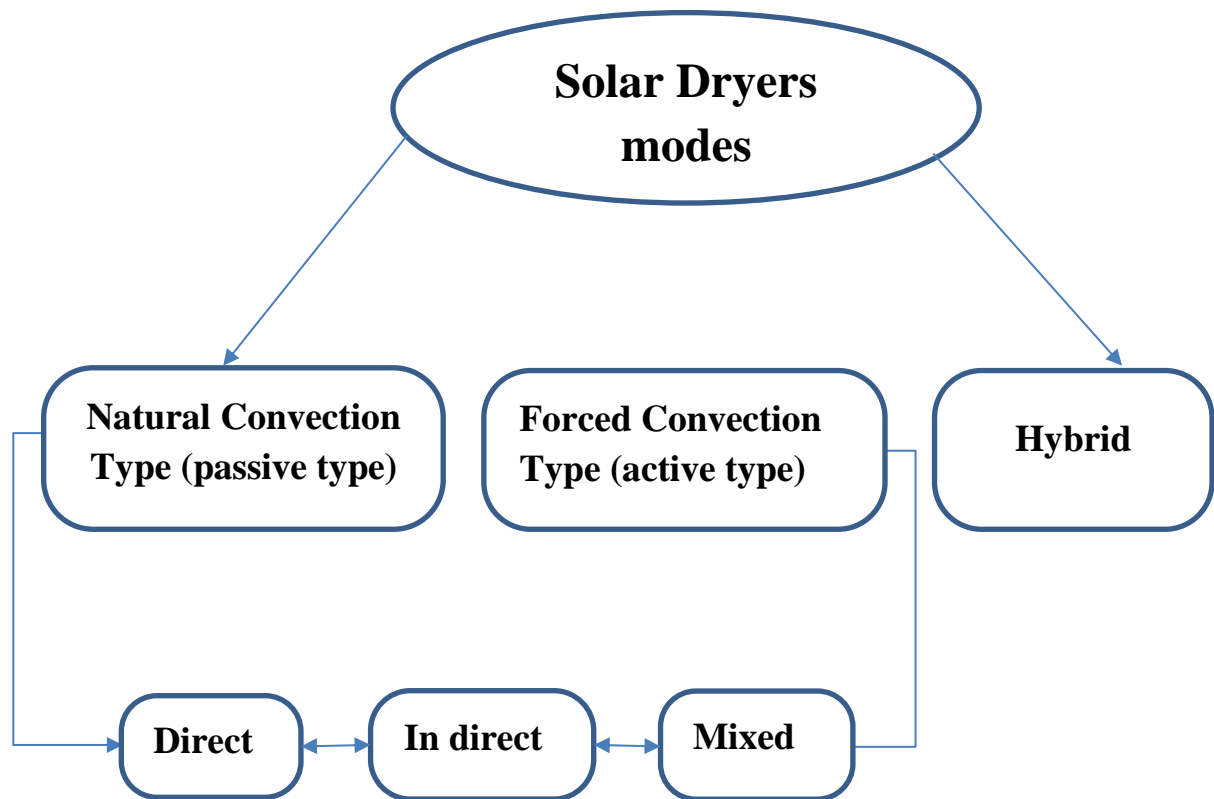


Figure I.4 :classification of solar dryers

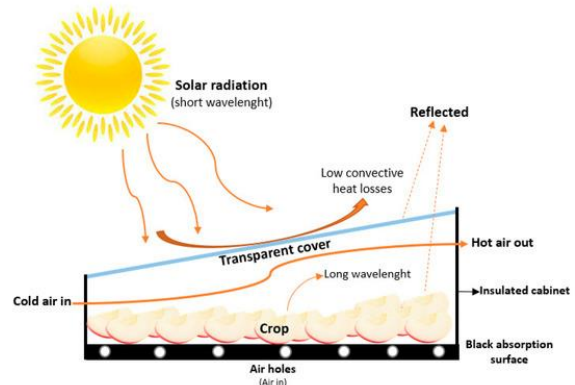
#### A. Natural Convection Type

In the natural type, no external factor is required to deliver heat for the dehydration of the product. Natural convection-type solar dryers may be direct, indirect, or mixed mode type[12]

- **Direct Solar Dryer**

In direct solar dryers, the product is exposed directly to sunlight so that it can be simply dehydrated. In this type of solar dryer, a black painted heat absorbing plate is provided that can collect and absorb the sunlight and convert it into heat. The product to be dried is placed

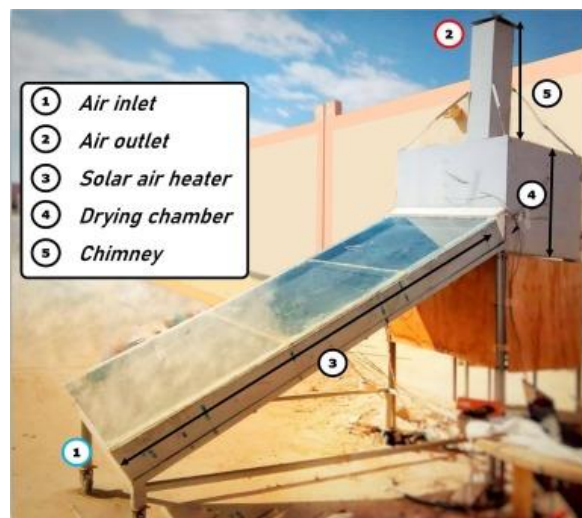
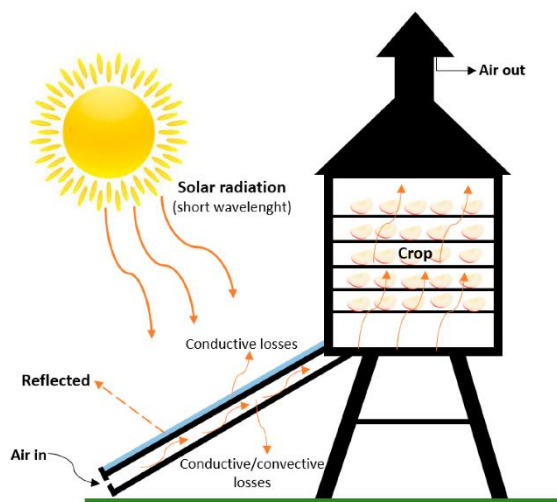
directly on the absorber plate. This dryer may have glass lid covers and vents to increase thermal efficiency.[6]



**Figure I.5:** Direct solar dryer (LENREZA UKM Ouargla Laboratory)

### Indirect Solar Dryer

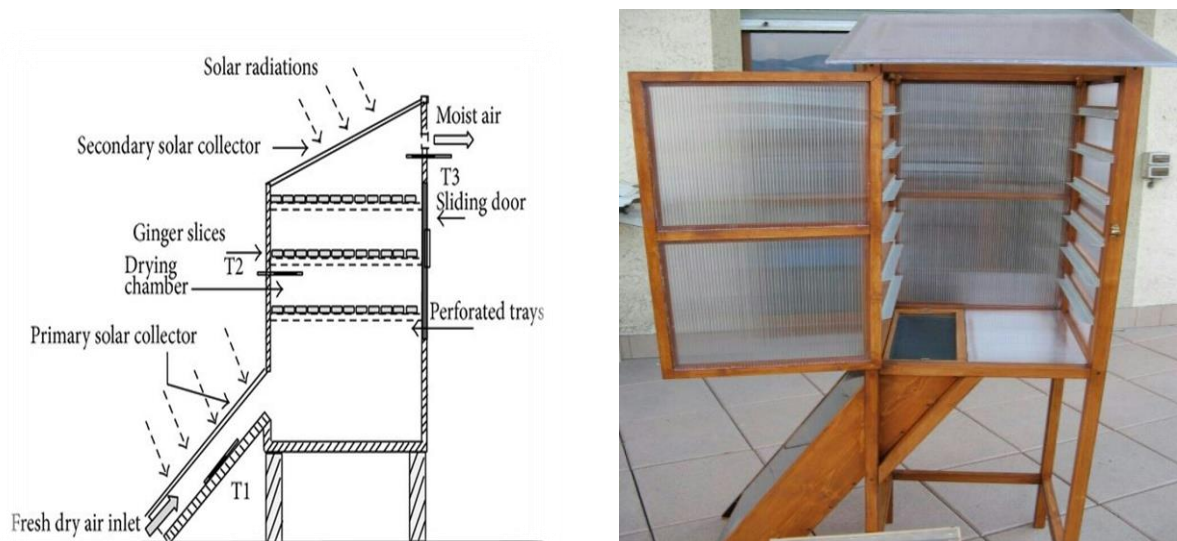
In indirect solar dryers, the products are not directly exposed to solar radiation and are instead shielded from light, which helps preserve their nutritional quality. These dryers typically comprise two main components: a solar collector and a drying chamber (Figure I.3) [20]. The solar collector, usually positioned separately and connected to the drying chamber during operation, is inclined to optimize solar energy absorption. It consists of a transparent glass cover and an absorbing surface, often painted black to enhance heat absorption. Air is heated as it passes through the solar collector, then directed into the drying chamber. During this process, heat is transferred from the hot air to the product, while moisture is transferred from the product to the air [21][6].



**Figure I.6:** indirect solar dryer

- **Mixed Mode Dryer**

The mixed-mode solar dryer is a combination of indirect and direct solar mode solar dryer is a combination of indirect and direct solar dryer. This works under the combined action of the solar intensity incident on the product to be dried and the air preheated in the solar collector provides the heat needed for the drying process. A diagram of a mixed-mode solar dryer is shown in Fig . under the combined action of the solar intensity incident on the product to be dried and the air preheated in the solar collector provides the heat needed for the drying



**Figure I.7:** Mixed-mode solar dryer

## B. Forced Convection Type

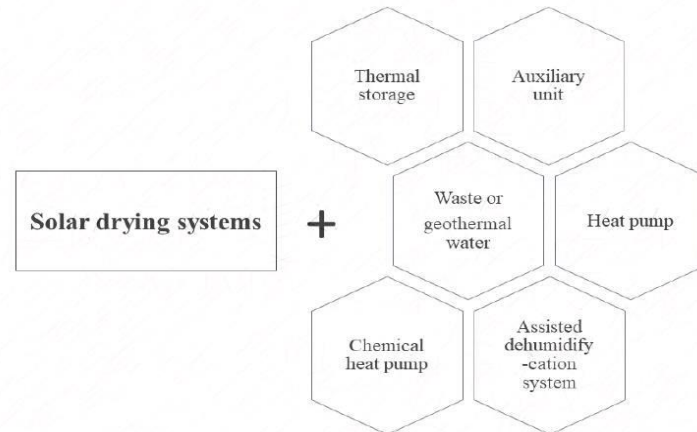
Operation and types of these dryers are identical to natural convection dryers, but with an additional fan/blower that blows hot air continuously over the products to be dried, resulting in much faster and more efficient drying. Relatively these dryers are thermodynamically competent and could be used to dry a wide range of agricultural products.[12]

- **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 [13][22].



**Figure I.8:** Solar drying systems with various heating systems[22]

## I.5 Phase Change Materials

### I.5.1 Definition of Phase Change Materials

Phase Change Materials PCM are materials that accumulate energy when changing from solid to liquid state (melting heat) and turn it over when changing from liquid to solid state (solidification heat). Phase change heat exhibits a high heat density and a minimum temperature variation during fusion and solidification periods. A phase change material is a solid that stores energy by melting upon the application of heat. The melting temperature may be fixed or vary over a small range. The stored energy is recovered upon solidification of the liquid.[6]

### I.5.2 Role of PCM in Solar Dryers:

Phase Change Materials (PCMs) play a crucial role in enhancing the performance and efficiency of solar dryers. Here's how:

#### A. Thermal Energy Storage

Phase Change Material absorb excess heat during the day when solar radiation is strong. As they melt, they store this thermal energy in the form of latent heat. Later, when sunlight

decreases (e.g., in the evening or on cloudy days), the PCM solidifies and releases the stored heat, maintaining the drying temperature.[14]

### B. Continuous Drying Process

By stabilizing the internal temperature of the dryer, PCMs help to continue the drying process even when solar energy is unavailable. This leads to more uniform and faster drying, improving product quality.[14]

### C. Temperature Regulation

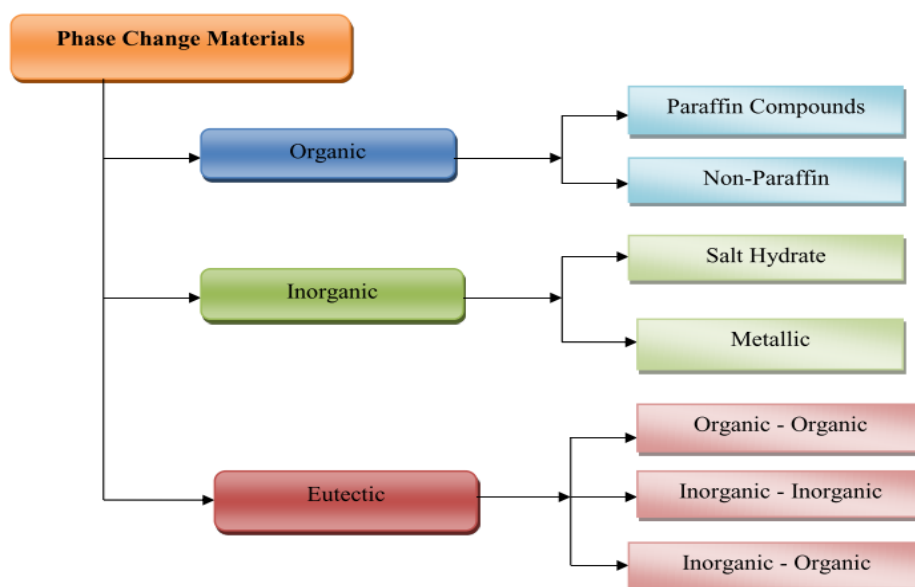
Phase Change Materials help prevent temperature fluctuations inside the drying chamber, protecting heat-sensitive products from overheating and degradation.[14]

### D. Energy Efficiency

They improve the overall energy efficiency of the system by reducing heat loss and utilizing stored energy effectively, which can reduce drying time and cost.[14]

## I.5.3 Classification of Phase Change Materials (PCMs):

A large number of phase change materials (organic, inorganic, and eutectic) are available in all required temperature ranges. [2]



**Figure I. 9:** Classification of Phase change Materials[2]

- **Organic materials**

Most organic PCMs investigated are paraffins and fatty acids. It is found that paraffins have good thermal and chemical stability after several thermal cycles. The fatty acids studied widely

are stearic, lauric, myristic, capric, and palmitic acids. Most of the fatty acids used as PCMs are industrial grade.[6]

- **Inorganic materials**

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

- **Hydrated salts:**

The general formula of a hydrated salt is  $AB \cdot nH_2O$  ( $AB$  = 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  $CaCl_2 \cdot 6H_2O$ . [2]

- **Eutectic**

PCM A eutectic PCM is a combination of two or more compounds that are either organic, inorganic, or both. In the last decade, many researchers have shown significant interest in new eutectic-type PCMs instead of pure compounds. It is observed that most of the organic and inorganic eutectics that are proposed as PCMs are made from fatty acids and salt hydrates, respectively.[6]

## **I.6 Paraffin Wax**

Paraffin wax, with a melting point of around  $60\text{--}65^\circ\text{C}$ , is utilized in direct solar dryers as a phase-change material (PCM) to store thermal energy when solar radiation is high. As solar radiation decreases, the paraffin wax solidifies and releases the stored heat, helping to maintain a consistent temperature inside the dryer. This process improves efficiency, extends drying time, and ensures a controlled drying environment. In this case, with 20 blocks of paraffin wax, each weighing 200 grams, the total weight amounts to  $4 \cdot 10^3$ g grams, this plays a key role in enhancing the dryer's performance.



**Figure I. 10:** Iron cans for paraffin wax

Recent Developments:

- ❖ Embedding PCMs in heat exchangers within or beneath drying chambers.
- ❖ Use of encapsulated PCMs to improve thermal conductivity.
- ❖ Integration with sensors to regulate drying temperature based on PCM activity.[16]

**Table I.1:** Summary Table

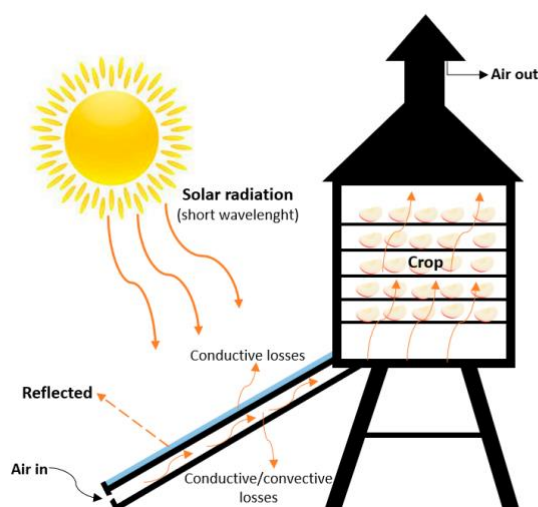
Feature	Indirect Solar Dryer	PCM-Enhanced Indirect Dryer
Drying Efficiency	Medium	High (due to extended drying hours)
Drying Time	Weather-dependent	More stable; shorter total time
Energy Use	Solar only	Solar + stored thermal energy
Temperature Control	Moderate	Excellent
Cost	Lower initial cost	Higher due to PCM materials
Product Quality	High	Very high

## 9. Literature Review:

In this section, we provide an overview of some studies conducted on indirect solar dryers.

The two primary forms of indirect sun driers are distributed and integrated systems. Compact, standalone devices that combine solar energy collection and drying capabilities are called integrated solar dryers. These dryers provide a number of advantages, including as low maintenance needs, lower capital expenditures, and simplicity of installation. But they also have drawbacks, like limited flexibility and drying capacity (Prakash and Kumar, 2013). An integrated indirect solar drier uses hot air heated by a solar collector that is connected to the drying chamber to dry the product. To reduce heat loss, the sides of the chamber are usually insulated. Faster drying rates made possible by this shape enhance the quality of the final product. Farmers frequently utilize integrated indirect dryers for small-scale output. The cabinet solar dryer displayed is a prime illustration of one of these dryers.

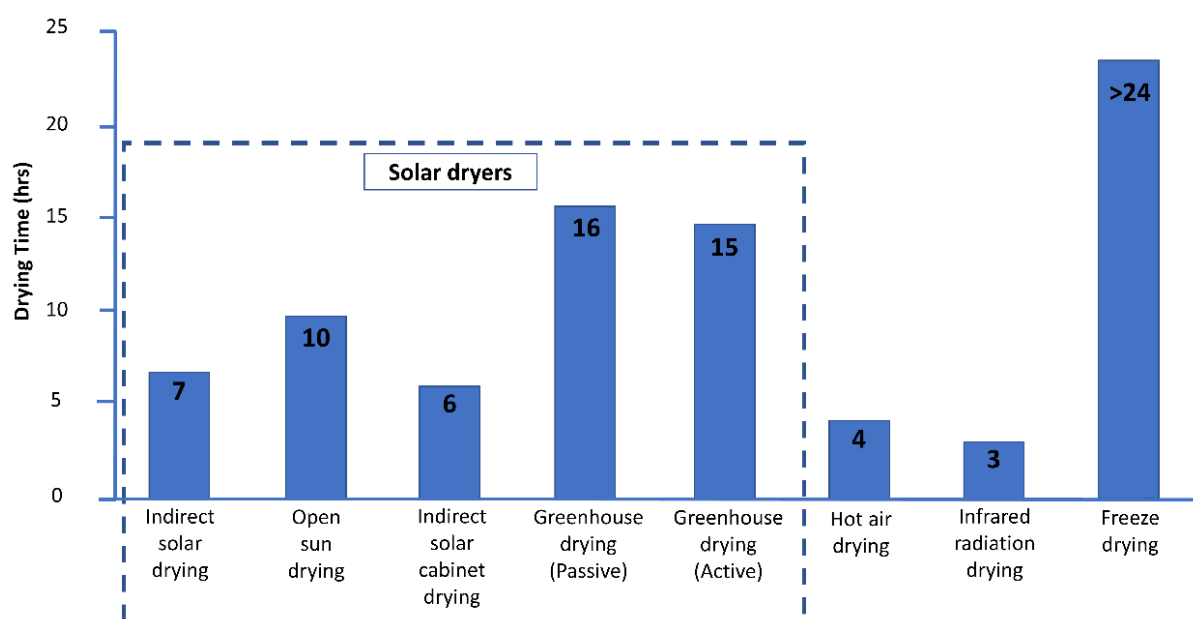
The principal differences between indirect solar dryer (ISD) and direct solar dryer (DSD) are in their heat transfer and vapor removal methods. In indirect solar dryers, the crops are placed in trays or shelves inside an opaque drying cabinet in an independent unit from the solar collector (Figure //).



**Figure I. 11:** Schematic of working principle of indirect drying method

Among the different systems of solar drying, the indirect type solar dryer (ISD) type ensures the best quality of dried products, texture, as well as maintains at best the fresh product color. The principle of the ISD is that the food is heated indirectly through the air coming from the solar air heater (SAH), not by direct exposure to sunlight (Messaoud; Sandali et al., 2019; P. Singh & Gaur, 2020). Due to the unique features of this type of solar dryers (i.e. ISD, (Lingayat et al. (Lingayat et al., 2020) discussed literature data of different configurations investigated by researchers used this technique. Parameters affecting the drying rate, types of energy storage used in the ISDs, and the important findings were listed and tabulated. In that recent paper, the authors concluded that a well-designed ISD with minimum operating and maintenance cost is necessary for an effective drying process. Many configurations and designs of ISDs have been

developed in the literature. The conventional type contains a SAH and drying chamber. The SAH allows solar irradiation conversion into thermal energy at the absorber which transfers the heated air to the chamber by natural or forced convection (Tarik Hadibi et al., 2021). The heated air triggers the evaporation of the water inside the product after absorbing the thermal energy carried by the air. In this case, the dried product can be easily stored in pressure and temperature conditions close to the ambient (Abhay et al., 2018). The advantages of the ISD were highlighted by Vijayan et al. (Vijayan, Arjunan, & Kumar, 2020). The reduced time in indirect solar drying was estimated by performing a comparison with alternative drying types. The drying time of bitter gourd slices using ISD was compared to drying the same product with other solar drying methods reported in the literature. The drying time reduced by 18 h compared to freeze drying, 10 h compared to greenhouse drying, and 4 h compared to open sun drying (Figure 1.2). On the other hand, the drying time was nearly halved by using the hot air and infrared radiation techniques. However, from an energetic point of view, these last two techniques require high energy/cost, thus their efficiency is low. Therefore, using the ISDs is an optimal solution to strike a balance between the quality of the dried products and the energy/cost invested

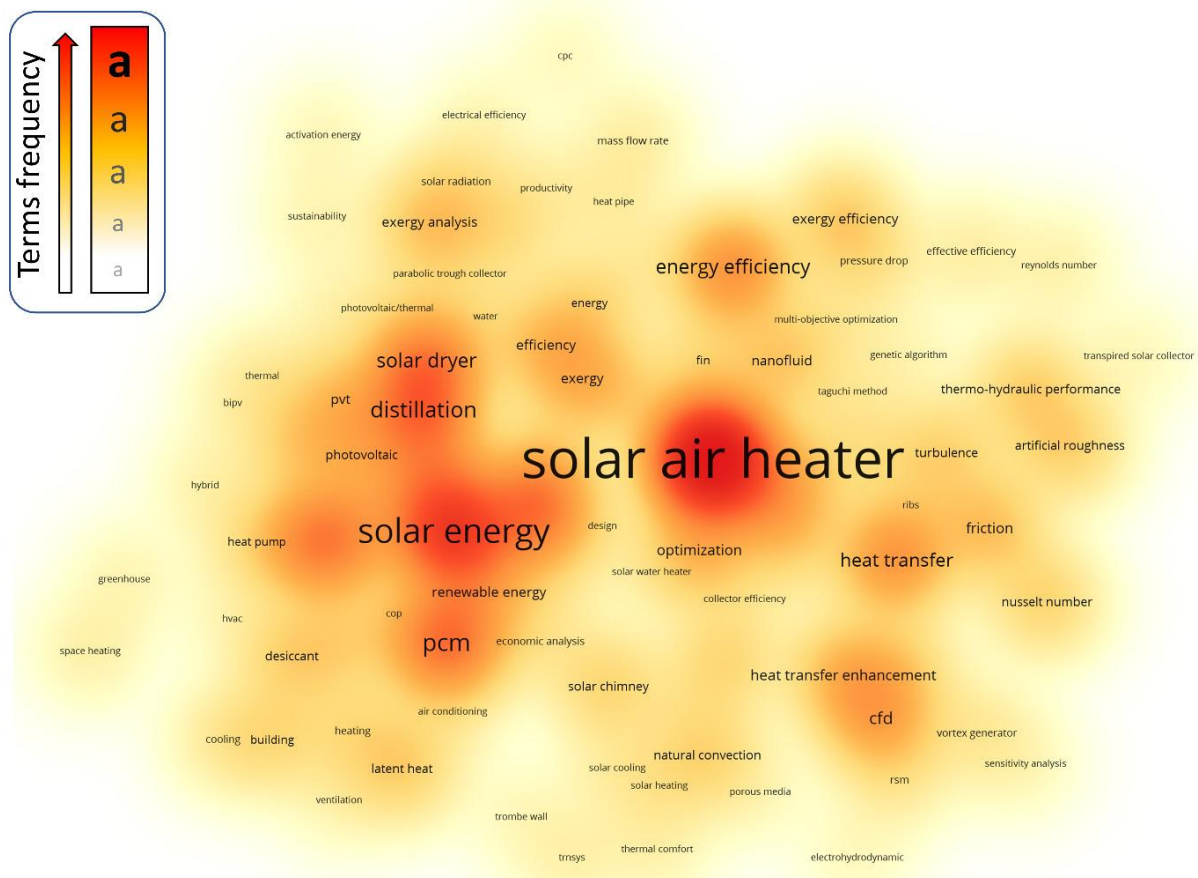


**Figure I.12:** Comparison of drying time of bitter gourd slices (Vijayan, Arjunan, & Kumar, 2020)

### I.9.1. Optimization of solar air heaters

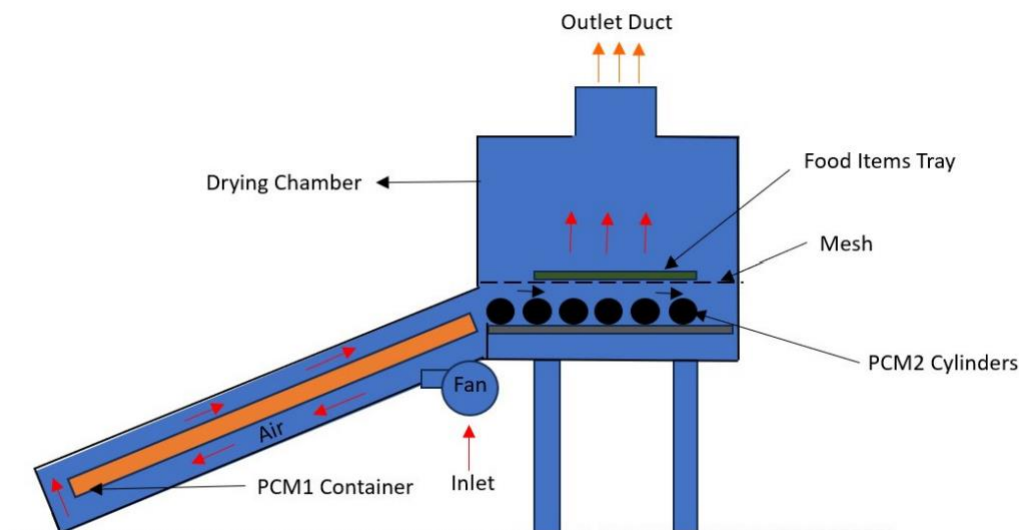
A popular method for characterizing how test variables affect output parameters (responses), determining how test factors relate to one another, and expressing the cumulative influence of all test factors in a given response is called Response Surface Methodology (RSM). Additionally, a well-designed RSM reduces the number of tests required to gather the greatest amount of data. Using RSM is crucial in contemporary industry, science, and engineering since physical tests and numerical simulations are used virtually everywhere these days as a tool for researching and improving systems and processes.





**Figure I.14:** Density visualization map derived from term analysis. The most commonly used terms refer to the intensity of red spots (nodes) and font size, as seen in the legend. Most commonly used terms (e.g., solar air heater) are highlighted in bold, large letter

Recently, there has been a surge in interest in bio-based PCMs that incorporate renewable materials like carbohydrates and proteins. Microencapsulated PCMs, as demonstrated in Figure I., have gained more attention. The material's thermal conductivity is enhanced and leakage is prevented by encapsulating PCMs into small particles within a protective shell or coating. It enhances its performance [7]. For instance, polymer encapsulated PCM, in which polymers are utilized to encapsulate the PCM. Hybrid PCMs are made up of two or more materials and enhance their thermal properties. Nanotechnology-based research involves incorporating nanoparticles into the PCM to improve their thermal properties and stability. The efficiency of solar collectors can be significantly enhanced through the use of nanofluids as phase change materials (PCMs) [8]. One advanced approach involves incorporating graphene into PCMs to improve their thermal conductivity and stability [9]. Mehling et al. [10] have explored the use of PCMs in a range of commercial applications, including solar dryers. The selection of suitable PCMs for different applications depends on their physical, chemical, and thermal properties, as well as their economic viability [11].



**Figure I.15:** Modified solar dryer with PCM placed inside collector and chamber

**Table I.2:** Desirable characteristics of PCMs

Thermal Properties	Physical Properties	Kinetic Properties	Chemical Properties	Economics Properties
High-level heat transfer rate	Good phase equilibrium	Supercooling should not take place	Chemically stable	Widely available
Greater latent heat of transition	Volume change is small	Sufficient crystallization rate	Non-toxic in nature	Cost-effective
Appropriate phase transition temperature	Vapor pressure is low		Good compatibility with materials	Abundant
			No fire hazard	

## Conclusion

This chapter compiles the various methods that researchers have employed to better the designs of solar dryers and increase the consistency of the dried items. Thorough bibliometric research has identified the flaws in solar drying systems. In this thesis, the indirect solar dryer type is mostly chosen as the best option to balance the energy/cost expenditure with the quality of the dried items. Additionally, the most pertinent approaches that researchers have employed to create solar drying systems are explained. Furthermore, this chapter has provided a comprehensive overview of phase transition materials, including their classification, use, and application. The following chapter will present the geometry of the topic under study.

# Experimental setup

## II Experimental setup

### II.1 Introduction

This chapter discusses the materials and methods used in the development and design of the indirect solar dryer, focusing on the key components and technologies that form the foundation for understanding and effectively applying solar drying techniques. It provides a detailed overview of the experimental setup and emphasizes the importance of accurate measurements to ensure reliable results.

The chapter presents a clear description of the actual design of the solar dryer, including its dimensions, the materials used, and the configuration of its parts. Special attention is given to the criteria for selecting materials, considering factors such as durability, cost-effectiveness, and thermal efficiency. One of the key features highlighted in this chapter is the integration of Phase Change Materials (PCMs), which play a crucial role in enhancing the dryer's performance. PCMs store thermal energy during periods of sunlight and release it when solar radiation is unavailable, allowing the drying process to continue more efficiently and consistently. Overall, this chapter serves as a comprehensive guide for researchers and engineers, supporting the development and wider adoption of indirect solar drying technologies by improving thermal performance and system reliability using advanced materials like PCMs.

### II.2 Description of the Prototypes:

The drying chamber is the main part of the proposed solar dryer. It is made of iron and supported by four legs, each with a height of 3.60 m. As shown in Figure 1, the drying chamber has a door and a chimney on top to allow the hot and humid air to escape.

The heating chamber is connected to one side of the drying chamber. It is a hollow, rectangular box with a transparent glass cover on top that is 2 mm thick. This glass allows sunlight to enter the chamber. Inside the heating chamber, there is a flat-plate solar collector that absorbs sunlight and turns it into heat. The heating chamber stands on four legs—two on one side and two in the middle. It has a width of 2.70 m and is tilted at an angle of 33 degrees to the ground so it can capture more sunlight.

The design of the solar dryer was based on the following points:

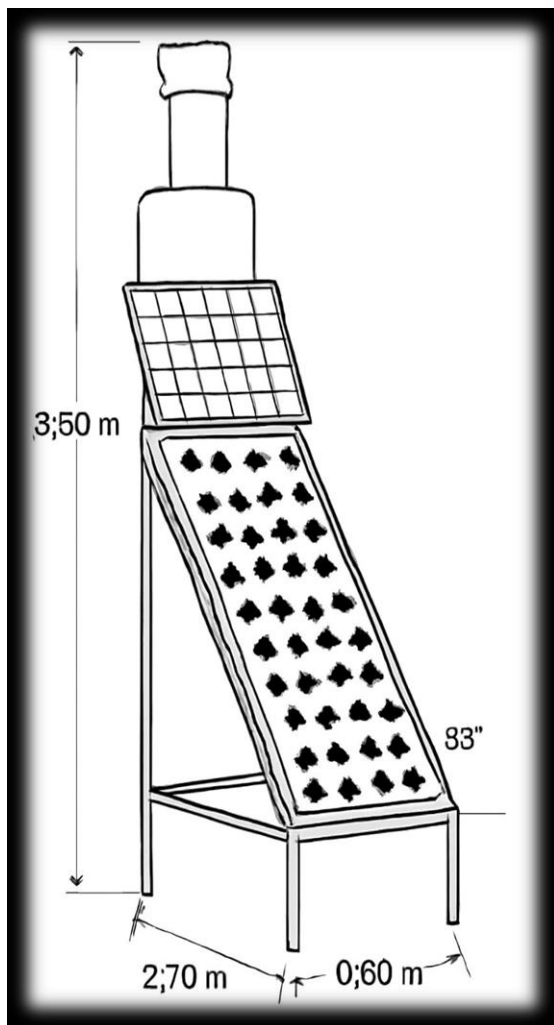
- ❖ The amount of moisture to be removed from a certain amount of lemons.
- ❖ The time needed to complete the drying process.
- ❖ The average daily hours of sunlight to estimate the total drying time.
- ❖ The amount of air needed for drying.
- ❖ The average daily solar radiation to estimate the energy input.
- ❖ The air mass flow rate inside the drying and heating chambers.

The solar dryer was built to work with indirect natural convection, meaning the product does not receive sunlight directly. The body of the dryer is made from an iron barrel that is 1 meter long, covered with rock wool for insulation, and wrapped in aluminum. The dryer has three main parts: the solar air heater (heating chamber), the drying chamber, and an aluminum box.

In this experiment, a newly designed solar dryer was used. It includes Phase Change Material (PCM) to store heat. This design is simple and can be used by people in rural areas without technical knowledge. PCM can absorb and release heat when it changes between solid and liquid states. This helps keep the dryer working even when the sun is not shining.

The system is directed toward the south to face the midday sun, with the heating chamber and solar collector tilted at 33 degrees. A fan moves the hot air from the heating chamber to the drying chamber, where it heats the products using convection. The glass cover keeps the heat inside, and the natural airflow removes hot, moist air through the trays holding the crops.

PCM stores extra heat during the day and releases it later, helping to continue the drying process at night or during cloudy periods. The main goals of this system are to extend drying time, make better use of solar energy, reduce moisture loss, and prevent microbial damage to the dried product.



**Figure II.16:**the indirect solar dryer

## II.3 Materials used for the greenhouse-type direct solar dryer:

### II.3.1 Iron:

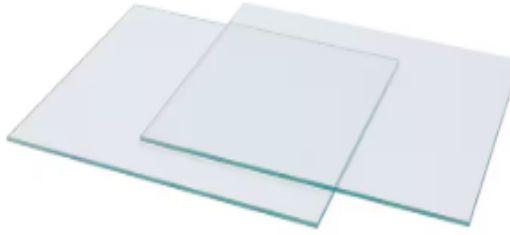
Iron is a widely chosen material for various applications due to its advantageous properties. It is suitable for indirect solar dryers because of its good thermal conductivity, durability, cost-effectiveness, availability, and ease of welding.



**Figure II.17:**Iron used in the manufacture of the solar dryer

### II.3.2 Clear glass:

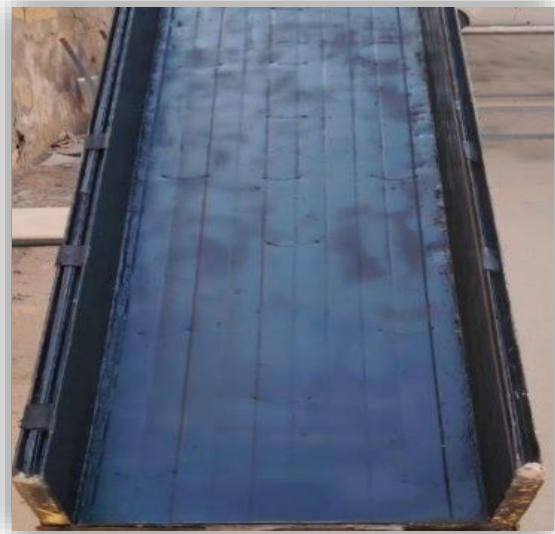
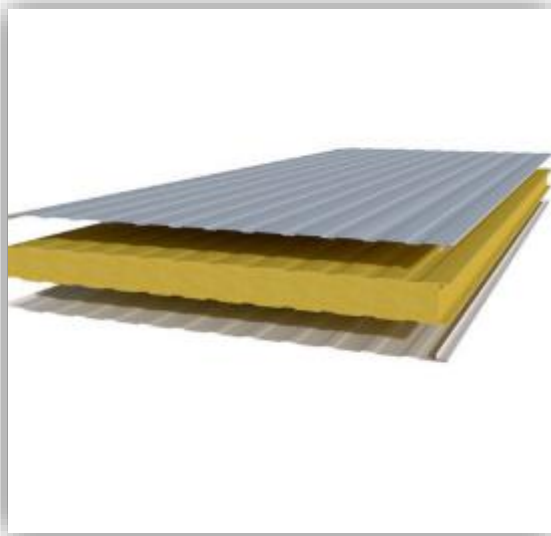
Is a transparent, durable, and lightweight material with UV resistance, thermal insulation, and safety features. Its properties make it an excellent choice for solar dryers, allowing sunlight penetration, withstanding weather conditions, and ensuring efficient and reliable drying.



**Figure II.18:** Clear glass

### II.3.3 Sandwich panel:

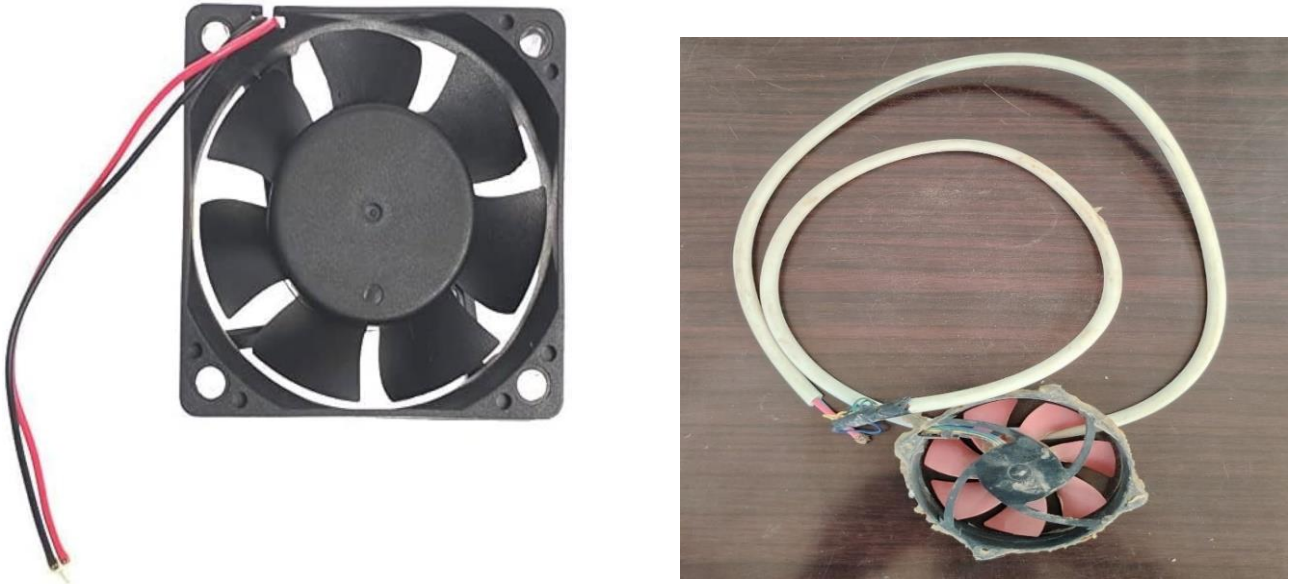
Sandwich panels are widely used in indirect solar dryers because of their excellent insulation properties, lightweight structure, and robust design. They provide high thermal efficiency, flexibility in customization, and long-lasting durability, making them a perfect choice for effective and dependable solar drying.



**Figure II.19:** Sandwich panel

### II.3.4 The fan:

The fan in an indirect solar dryer is crucial for airflow and efficient drying. It prevents stagnant pockets, distributes heat and moisture evenly, and removes moisture-laden air. This improves drying efficiency by facilitating moisture removal and preventing condensation.



**Figure II.20 :** The fan used in the indirect solar dryer

### II.3.5 Paraffin (PCM):

Paraffin is used in indirect solar dryers as a phase-change material, storing thermal energy during periods of high solar radiation. It solidifies when solar radiation decreases, releasing the stored heat and maintaining a consistent temperature inside the dryer. This improves efficiency, extends drying time, and provides a controlled drying environment.



**Figure II.21 :** The paraffin that was used in the thermal energy storage system

## II.4 Prototype Instrumentation

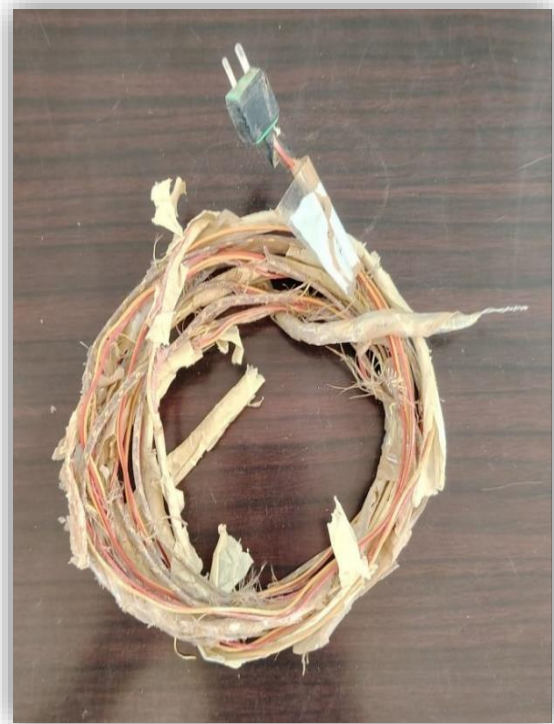
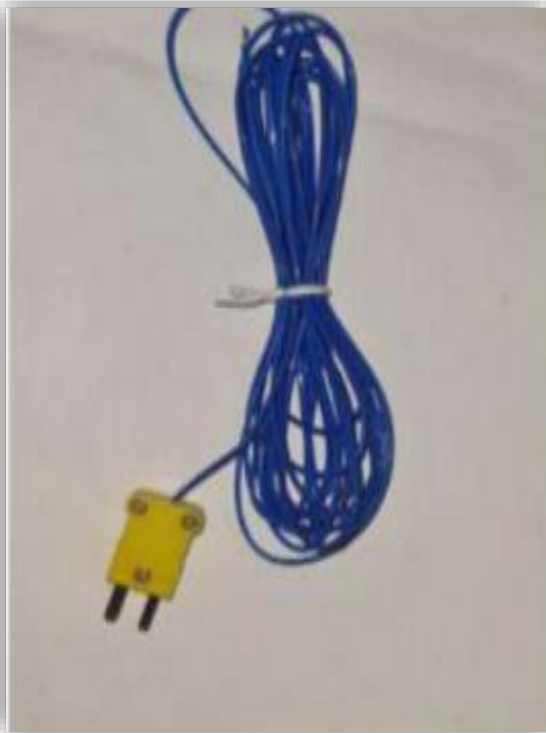
To improve the performance of the indirect solar dryer prototype, various operational parameters were measured and monitored. The instruments and tools used for measurement and data collection are listed below:

**Table II.3:** Prototype Instrumentation

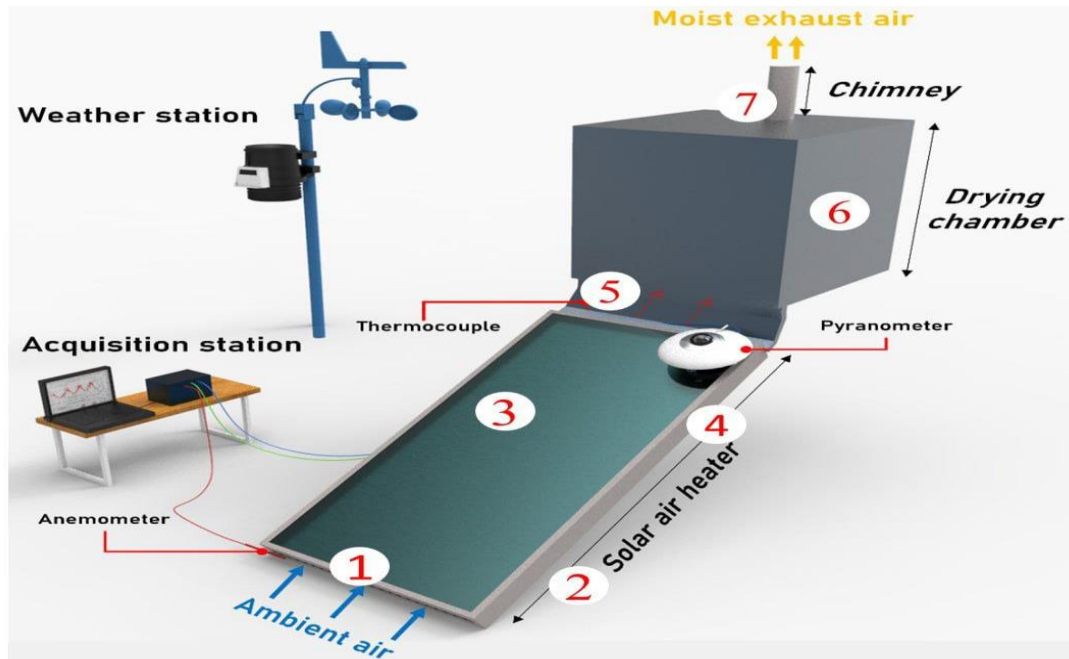
1- K-type nickel-chrome/nickel-aluminum thermocouples
2- Testo Model 440 anemometer
3- Keithley 2701 data acquisition system
4- BTM-4208SD: 12 channel temperature recorder + SD card data recorder
5- EKO and EPPLY type pyranometers
6- KERN PCB 3500-2 type balance and KERN ABT 220-4M balance

### II.4.1 Temperature Measurement:

Temperatures are measured using K-type nickel-chrome/nickel-aluminum thermocouples. These thermocouples can measure temperatures up to 750°C and provide an accuracy of 0.1°C (see Figure



**Figure II.22:** Thermocouples Nickel-Chrome/Nickel-Aluminium



**Figure II.23:** Location of thermocouples

#### II.4.2 Air velocity and humidity measurement:

The drying air velocity is measured at the outlet of the greenhouse-type solar dryer using a Testo Model 440 anemometer. The relative humidity is also measured using the probe of the Testo 610 thermo-hygrometer:



**Figure II.24:** Testo 440 anemometer + Testo 610 thermo-hygrometer

### II.4.3 Measurement of solar radiation:

The PCE-SPM 1 is a solar power meter with datalogging capabilities, used to measure the intensity of solar radiation in watts per square meter ( $\text{W}/\text{m}^2$ ). It provides real-time readings and is suitable for solar energy research, photovoltaic system analysis, and the evaluation of indirect solar dryer performance. During the measurements, the device was oriented at a 33-degree tilt angle facing south to accurately capture the solar radiation falling on the collector surface. It features internal memory for data storage and a user-friendly interface for logging and reviewing data over time with high accuracy.



**Figure II.25 :** Solar Power Meter (PCE-SPM 1)

#### II.4.4 Lutron Gm-500 Digital Scale, 500g X 0.1g, Rs-232:

This is a measuring instrument used to track the mass during drying (Figure II.26 ):



Figure II.26: Lutron gm-500 digital scale, 500g x 0.1g, rs-232

#### II.4.5 Data Acquisition and Processing:

The system for acquiring and processing data includes a temperature recorder with 12 channels that is connected to 12 thermocouples. This system is used to gather and record data (see Figure II. 27)



Figure II.27 : Photograph of the 12-channel temperature recorder

## II.6 Raw Materials

**Lemon:** Lemon is a citrus fruit known for its refreshing, tangy taste and numerous health benefits. It is an excellent source of vitamin C, which plays a vital role in boosting the immune system, promoting skin health, and protecting cells from free radical damage. Lemons also contain other important nutrients such as vitamin B6, folate, and potassium. Additionally, lemons are rich in antioxidants, which support overall health by reducing inflammation and fighting oxidative stress. With their high water content and low calorie count, lemons are a great addition to the diet, helping with hydration and digestion. Incorporating lemon into meals and beverages can enhance flavor while providing essential nutrients.



**Figure II. 28:**Lemon that was used for drying

## II.7 Drying protocol:

Preparation of Lemon samples:

To achieve the best results in drying lemons, we start by selecting fresh lemons and ensuring they are clean. Next, the lemons are thoroughly washed to remove any dirt or impurities. The following step is to slice the lemons into thin slices, approximately 2 mm thick, to ensure even drying. After slicing, the lemon slices are weighed to determine the quantity and ensure accuracy in the process. Finally, the slices are placed in a designated drying area until they are completely dried, resulting in high-quality dried lemons.

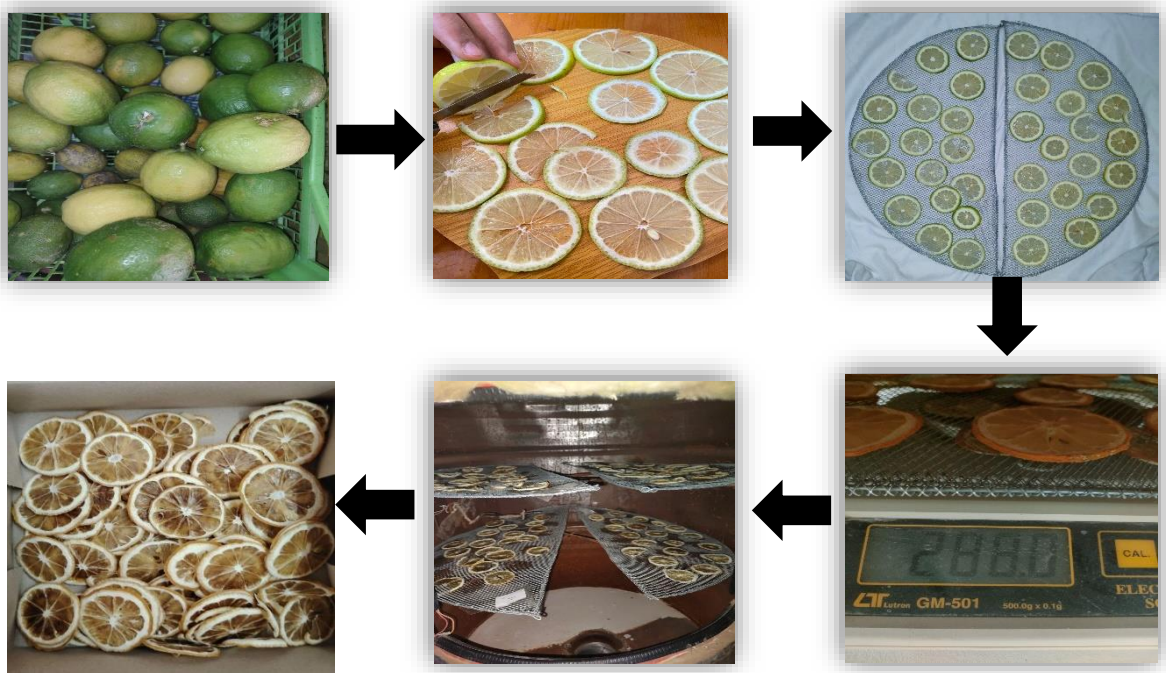


Figure II.29: Steps to prepare dried lemon

## II.8 EXPERIMENTAL PROCEDURE:

We have done four experimental tests .It was conducted over four consecutive days to evaluate the technical performance and thermal behavior of various configurations of the study solar dryer.

### II.8 .1 The first Case:

The 1<sup>st</sup> experiment took place on May 05th, 2025, under clear skies, using natural convection, from 9:00 a.m. to 17:00 p.m. A lemon sample weighing 383.9 g was used for the drying process, divided into trays inside the drying chamber. Seven K-type thermocouples were employed to monitor and log the temperature at various points within the TSC(fig: II.30) and the drying chamber. Solar radiation was consistently monitored throughout the drying process, along with air velocity and ambient temperature, using an air quality measurement device, as illustrated in (Fig: II.31). The lemon mass was recorded every 1:00 hour using a digital scale with a 0.1 g accuracy(fig: II.32). Once the drying was complete, the dried lemons were manually removed from the chamber and quickly sealed in an airtight container for storage.

### Theory of calculation:

- The moisture content: it is calculated using the following formula:

$$MC = m(initial) - \frac{m(final)}{m(initial)} \% \quad (1)$$

Where:

$W(\%)$  is the moisture content on a wet basis in %.

$m(initial)$  is the mass of the sample before being placed in the oven (in grams).

$m(final)$  is the mass of the sample after being placed in the oven (in grams).

- The moisture rate: it is drying curves involves determining a characteristic drying equation of the form:  $MR = f(t)$

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (2)$$

Where  $M_t$ ,  $M_e$ , and  $M_0$  are the values of the moisture content (dry basis) at time  $t$ , at infinity (equilibrium), and at  $t = 0$ , respectively. The drying rates were calculated using the following equation.

- Dryier Rate (DR):

$$DR = \frac{M_i - M_f}{dt} \quad (3)$$

rying Rate (DR) is the amount of moisture removed from a wet material per unit of time during the drying process.

$W_i$  : Initial weight of the material (before drying)

$W_f$  : Final weight of the material (after drying)

$dt$ : Drying time

- The useful power recovered by the fluid is determined by the following equation:

$$Q_u = \dot{m} \cdot C_p \cdot (T_s - T_c) \quad (4)$$

With:

- $\dot{m}$  : Mass flow rate [ $kg/s$ ].
- $C_p$  : Specific heat capacity of air [ $J/kg^\circ C$ ].
- $T_c$  : Inlet temperature [ $^\circ C$ ].
- $T_s$  : Outlet temperature [ $^\circ C$ ].
- $A_c$  : Surface area of the greenhouse base [ $m^2$ ].
- $I$  : Incident solar power ( $W/m^2$ ).
- $\tau_c$  : Transmissivity coefficient of the covering ( $\tau_c$ -polycarbonate = 0.7)
- Thermal efficiency:

The thermal efficiency can be calculated using the following equation [56]:

$$\eta_{th} = Q_u / (I \cdot A_c \cdot \tau_c) \quad (5)$$

### II.8.2 The second Case:

The 2<sup>nd</sup> experiment took place on May 18th, 2025, under clear skies, using forced convection by integrating the PV cells, from 9:00 a.m. to 17:00 p.m. A lemon sample weighing 500.2 g was used for the drying process, divided into trays inside the drying chamber. Seven K-type thermocouples were employed to monitor and log the temperature at various points within the TSC(fig: II.33) and the drying chamber. Solar radiation was consistently monitored throughout the drying process, along with air velocity and ambient temperature, using an air quality measurement device, as illustrated in (FigII.34). The lemon mass was recorded every 1:00 hour using a digital scale with a 0.1 g accuracy(fig: II.35). Once the drying was complete, the dried lemons were manually removed from the chamber and quickly sealed in an airtight container for storage.

#### Theory of calculation:

**MC:** same equation as (1)

**MR:** same equation as (2)

**DR:** same equation as (3)

- The useful power recovered by the fluid is determined by the following equation:

$$Q_{Total} = \dot{m} \cdot C_p \cdot (T_s - T_c) + E_{pv} \quad (6)$$

$E_{pv}$ : Electrical energy supplied by the PV panel to the fan [J]

$P_{pv}$ : Electrical power output of the PV panel [W]

$t$ : Duration of fan operation [s]

$$E_{pv} = P_{pv} \cdot t$$

- Solar panel characteristics:

Nominal Peak Power (0/+5W)  $P_{mpp}$  385 Wp

Open Circuit Voltage  $V_{oc}$  47.6 V

Short Circuit Current 10 A

Maximum Power Voltage  $V_{mpp}$  40.8 V

Maximum Power Current  $I_{mp}$  9.47 A

Maximum System Voltage 1500 V

Maximun Series Fuse Rating 20 A

- Thermal efficiency:

$$\eta_{th} = ( \dot{m} . Cp . (Ts - Tc) + E_{pv} ) / ( I . A_c . \tau_c ) \quad (7)$$

### II.8 .3 The Third Case:

The 3<sup>rd</sup> experiment took place on May 19th, 2025, under clear skies, using forced convection by integrating the PV cells with (PCM), from 9:30 a.m. to 22:30 p.m. A lemon sample weighing 640 g was used for the drying process, divided into trays inside the drying chamber. Seven K-type thermocouples were employed to monitor and log the temperature at various points within the TSC(fig: II.36) and the drying chamber. Solar radiation was consistently monitored throughout the drying process, along with air velocity and ambient temperature, using an air quality measurement device, as illustrated in (Fig: II.37). The lemon mass was recorded every 1:00 hour using a digital scale with a 0.1 g accuracy(fig: II.38). Once the drying was complete, the dried lemons were manually removed from the chamber and quickly sealed in an airtight container for storage.

#### Theory of calculation:

**MC:** same equation as (1)

**MR:** same equation as (2)

**DR:** same equation as (3)

- The useful power recovered by the fluid is determined by the following equation:

$$Q_{Total} = ( \dot{m} . Cp . (Ts - Tc) + m . Lf + \dot{m} . Cp . (Ts - Tc) ) + E_{pv} \quad (8)$$

- Thermal efficiency:

$$\eta_{th} = ( \dot{m} . Cp . (Ts - Tc) + m . Lf + \dot{m} . Cp . (Ts - Tc) + E_{pv} ) / ( I . A_c . \tau_c ) \quad (9)$$

#### II.8 .4 The Fourth Case:

The 4<sup>th</sup> experiment took place on May 20th, 2025, under clear skies, using natural convection integrated whit (PCM), from 9:00 a.m. to 22:00 p.m. A lemon sample weighing 488.7 g was used for the drying process, divided into trays inside the drying chamber. Seven K-type thermocouples were employed to monitor and log the temperature at various points within the TSC(fig: II.39) and the drying chamber. Solar radiation was consistently monitored throughout the drying process, along with air velocity and ambient temperature, using an air quality measurement device, as illustrated in (Fig:II.40). The lemon mass was recorded every 1:00 hour using a digital scale with a 0.1 g accuracy(fig: II.41). Once the drying was complete, the dried

#### Theory of calculation:

lemons were manually removed from the chamber and quickly sealed in an airtight container for storage.

**MC:** same equation as (1)

**MR:** same equation as (2)

**DR:** same equation as (3)

- The useful power recovered by the fluid is determined by the following equation:

$$Q_{Total} = (\dot{m} \cdot Cp \cdot (Ts - Tc) + m \cdot Lf + \dot{m} \cdot Cp \cdot (Ts - Tc)) \quad (10)$$

- Thermal efficiency:

$$\eta_{th} = (\dot{m} \cdot Cp \cdot (Ts - Tc) + m \cdot Lf + \dot{m} \cdot Cp \cdot (Ts - Tc)) / (I \cdot A_c \cdot \tau_c) \quad (11)$$

# Results and Discussions

### III Results and Discussions

#### III.1 Introduction

Solar drying is a sustainable, energy-efficient, and environmentally friendly technique for removing moisture from agricultural products while preserving their quality. By utilizing solar energy, this method reduces reliance on artificial heat sources, making it an economically viable solution for food processing and preservation. Solar drying can be categorized into direct and indirect methods. Direct solar drying exposes the product to direct sunlight, whereas indirect drying utilizes a separate heat source to warm the air that circulates through the drying chamber, protecting the product from direct exposure to sunlight.

This study explores four distinct solar drying techniques to evaluate their efficiency in drying lemon slices:

- Conventional indirect solar drying : In this method, the material is placed in a drying box where solar heat is used to remove moisture without direct exposure to sunlight. This technique relies on natural airflow to facilitate evaporation.
- Indirect solar drying with paraffin : This method integrates phase change materials (PCM), such as paraffin, to enhance heat retention. Paraffin absorbs and stores thermal energy, helping to regulate temperature fluctuations, especially in the afternoon when solar radiation declines.
- Indirect solar drying with a fan : A fan is incorporated to optimize airflow within the drying chamber, improving heat distribution and moisture evaporation by increasing air velocity.
- Combination of paraffin and a fan-assisted system : This method merges the benefits of PCM heat retention and mechanical airflow enhancement, aiming to create a more stable drying environment with improved moisture removal and drying efficiency.

To assess the effectiveness of each method, key parameters such as solar radiation, ambient temperature, drying rate, moisture content, air velocity, and internal temperature of the dryers are carefully monitored. Understanding these factors allows for the identification of the most efficient drying technique in terms of energy consumption and drying performance.

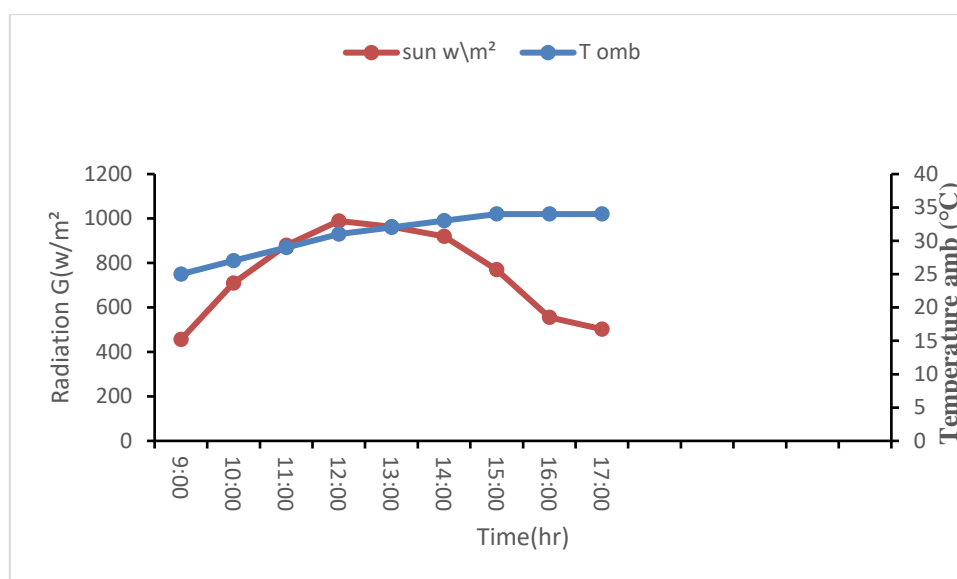
This study aims to provide insights into optimizing solar drying systems for improved efficiency, ensuring better moisture removal and uniform drying. By analyzing the interactions between solar radiation, heat retention mechanisms, airflow dynamics, and drying performance, we can develop strategies for maximizing energy efficiency and enhancing food preservation techniques.

### III.2 Conventional indirect solar drying:

In this method, the material is dried using solar heat without direct exposure to sunlight. The heat is transferred through a drying box.

#### III.2.1 Evolution of Solar Radiation and Ambient Temperature (06/05/2025)

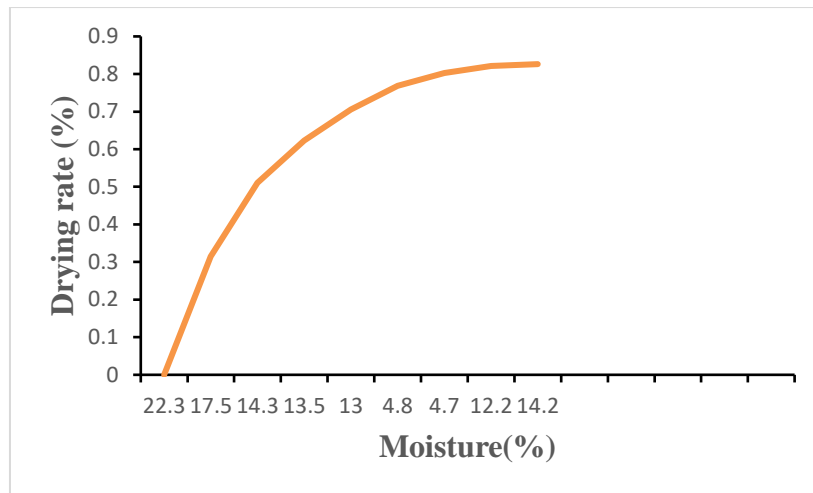
This graph illustrates the correlation between solar radiation ( $\text{W}/\text{m}^2$ ) and ambient temperature ( $T_1$ ) over the course of the day. Solar radiation gradually increases from morning until midday, reaching its peak around noon, which coincides with a rise in ambient temperature. In the afternoon, the temperature remains relatively stable as solar radiation begins to decline. This trend indicates that the drying process is most efficient during midday when solar radiation is at its highest, while drying efficiency diminishes as radiation levels decrease later in the day.



**Figure III.1 42:** Recorded daily solar radiation and ambient temperature evolution

#### III.2.2 Drying Rate as a Function of Moisture Content (06/05/2025)

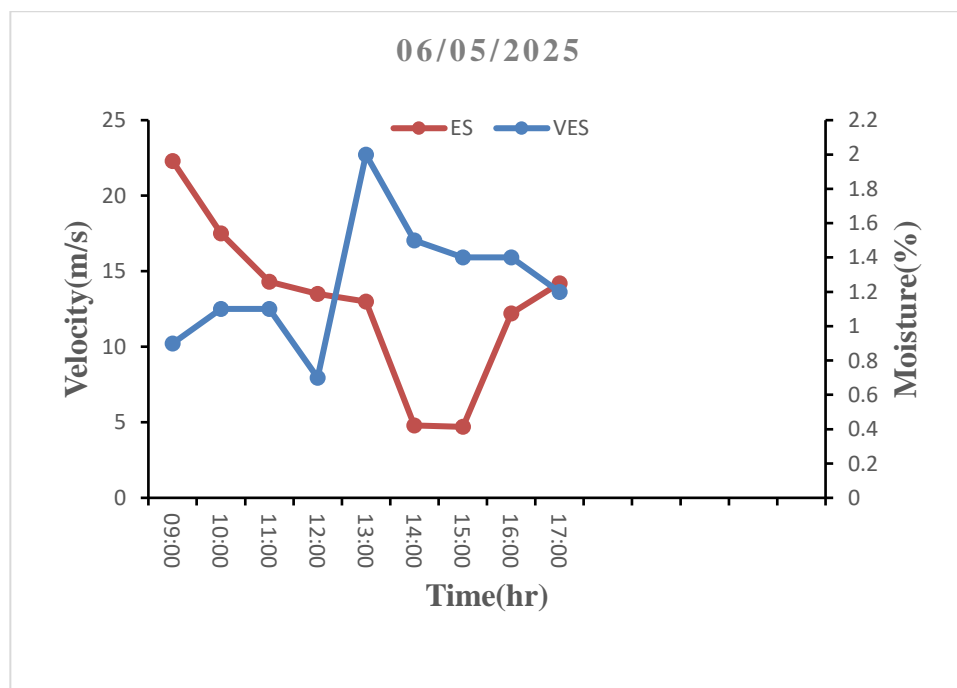
The drying rate curve demonstrates a rapid increase as moisture content decreases, a characteristic feature of the drying process. In the initial phase, when moisture content is high, the drying rate is steep due to the quick removal of water. However, as moisture content reduces, the drying rate gradually slows, reflecting the natural decline in drying efficiency as the material becomes drier. This suggests that the majority of moisture is evaporated early in the drying process, while further drying requires additional time and energy.



**Figure III.43:** Evolution of drying rate as a function of water content of lemon

### III.2.3 Evolution of Moisture and Air Velocity in the Solar Dryer (06/05/2025)

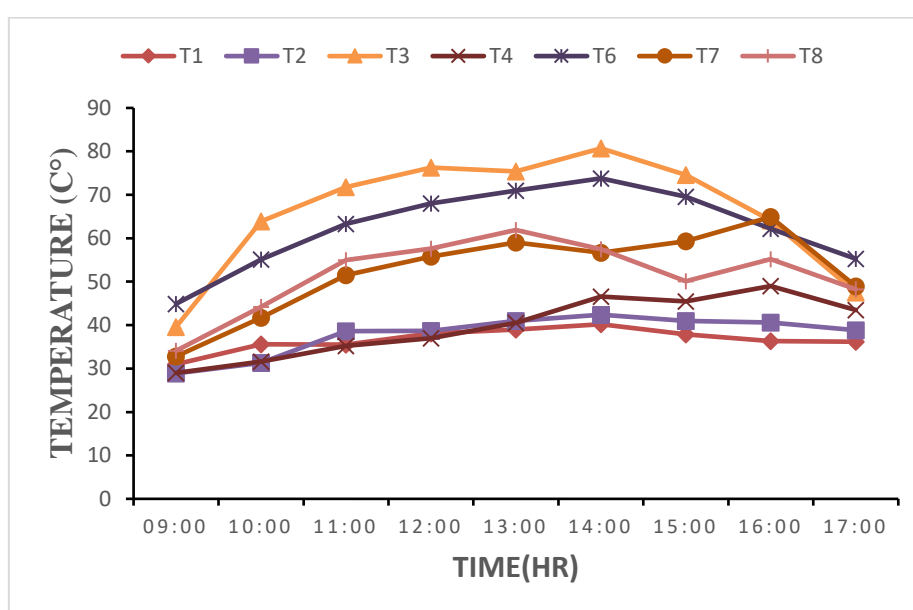
The graph illustrates an inverse correlation between moisture content (ES) and air velocity (VES), a characteristic trend in drying processes. As air velocity increases, moisture content decreases, highlighting the role of airflow in moisture evaporation. The significant variations in air velocity throughout the day indicate that external factors, such as fluctuating sunlight intensity and changing airflow conditions, play a crucial role in drying efficiency. The progressive reduction in moisture content as air velocity rises underscores the improved drying performance at higher airflow rates.



**Figure III.44:** Evolution of moisture and air velocity of the solar dryer during the drying of lemon

### III.2.4 Evolution of Internal Temperature in the Dryers (06/05/2025)

The temperature profile reveals a steady increase in the internal temperature of the dryer over the day, with a peak occurring around midday. Temperature readings are higher at points closer to the heat source (T1 to T4), whereas areas farther away (T7 and T8) register lower temperatures. This temperature gradient, typical in solar dryers, reflects uneven heat distribution. The variations in temperature across different sections suggest that enhancing heat distribution within the dryer could optimize drying efficiency and ensure a more uniform drying process.



**Figure III.45:** Evolution of the internal temperature of the dryers (with and without) during the days from 06/05/2025

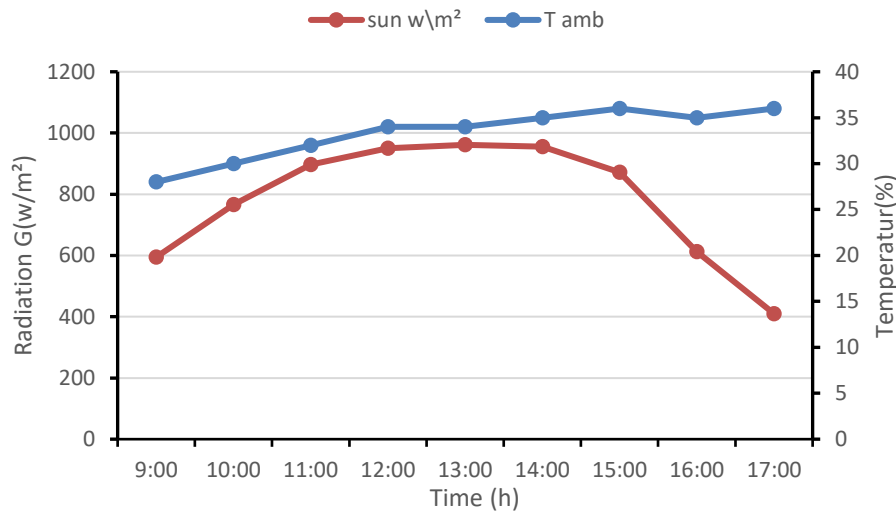
### III.3 Indirect solar drying with a fan:

In this case, the material is exposed directly to sunlight, but a fan and an air extractor are used to remove excess air and improve airflow around the material.

#### III.3.1 Evolution of Solar Radiation and Ambient Temperature (18/05/2025)

The graph illustrates the daily progression of solar radiation ( $\text{W}/\text{m}^2$ ) and ambient temperature (T1). Solar radiation rises steadily in the morning, reaching its peak around noon before gradually declining. Ambient temperature (T1) follows a similar trajectory, increasing as solar radiation intensifies. This direct correlation between solar energy and temperature plays a crucial role in the drying process. The decrease in radiation and temperature after midday

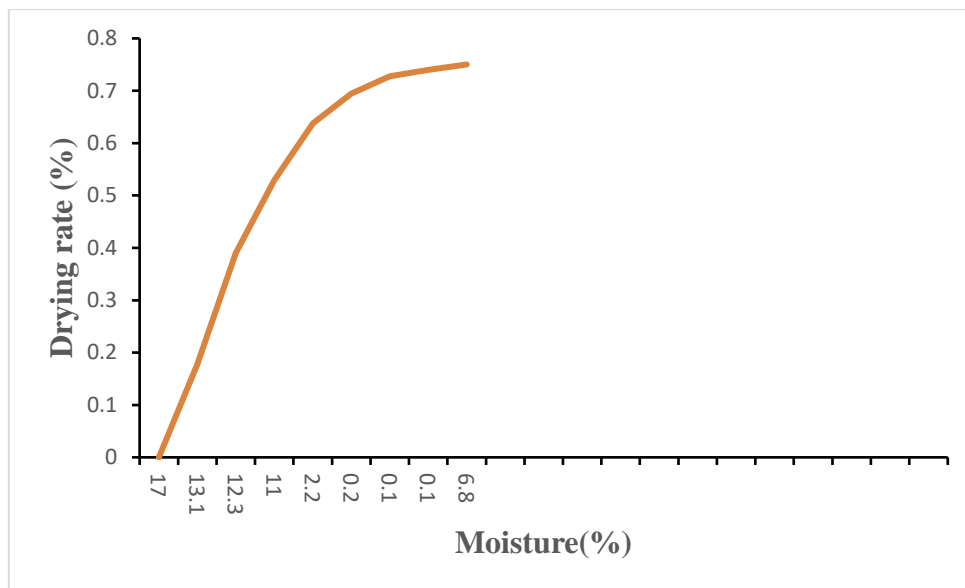
signals a reduction in drying efficiency, emphasizing the importance of optimizing drying times during peak solar radiation.



**Figure III. 46:**Recorded daily solar radiation and ambient temperature evolution

### III.3.2 Drying Rate as a Function of Moisture Content (18/05/2025)

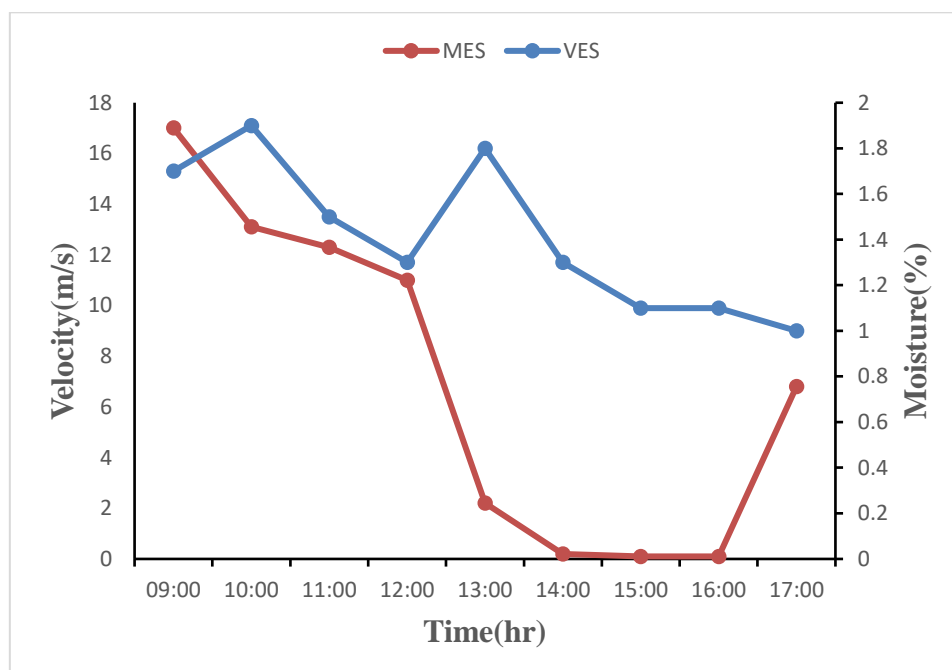
The curve depicts a typical drying process, showing a rapid increase in drying rate as moisture content decreases. During the initial drying phase, when moisture content is high, evaporation occurs quickly, resulting in a steep drying rate. However, as moisture levels drop, the drying rate gradually slows, reflecting the reduced efficiency of moisture removal. This trend is characteristic of drying processes and highlights the necessity of maximizing efficiency in the early stages when moisture is more readily available.



**Figure III.47:** Evolution of drying rate as a function of water content of lemon

### III.3.3 Evolution of Moisture and Air Velocity in the Solar Dryer (18/05/2025)

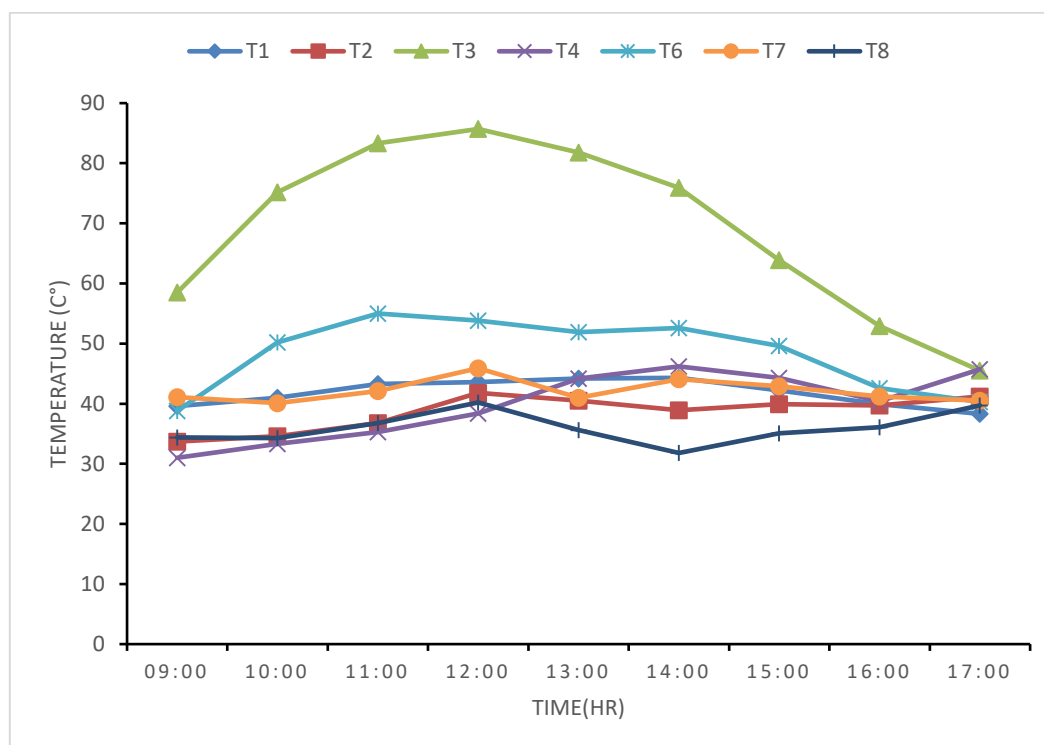
This graph illustrates an inverse correlation between moisture content (MES) and air velocity (VES), a characteristic trend in drying processes. As air velocity increases, moisture content decreases, signifying enhanced moisture removal due to stronger airflow. The sharp decline in moisture content around midday coincides with heightened air velocity, emphasizing the efficiency of moisture evaporation at peak airflow rates.



**Figure III.48:** Evolution of moisture and air velocity of the solar dryer during the drying of lemon 18/05/2025

### III.3.4 Evolution of Internal Temperature in the Dryers (18/05/2025)

The temperature curve reflects variations in the dryer's internal temperature throughout the day, with a peak occurring around midday. Temperature readings are highest at points near the heat source (T3 and T4), whereas areas farther away (T7 and T8) exhibit lower temperatures, revealing thermal gradients within the drying chamber. This uneven heat distribution, typical of solar dryers, may lead to non-uniform drying. Optimizing heat dispersion across the chamber could enhance drying efficiency and promote more consistent moisture removal.



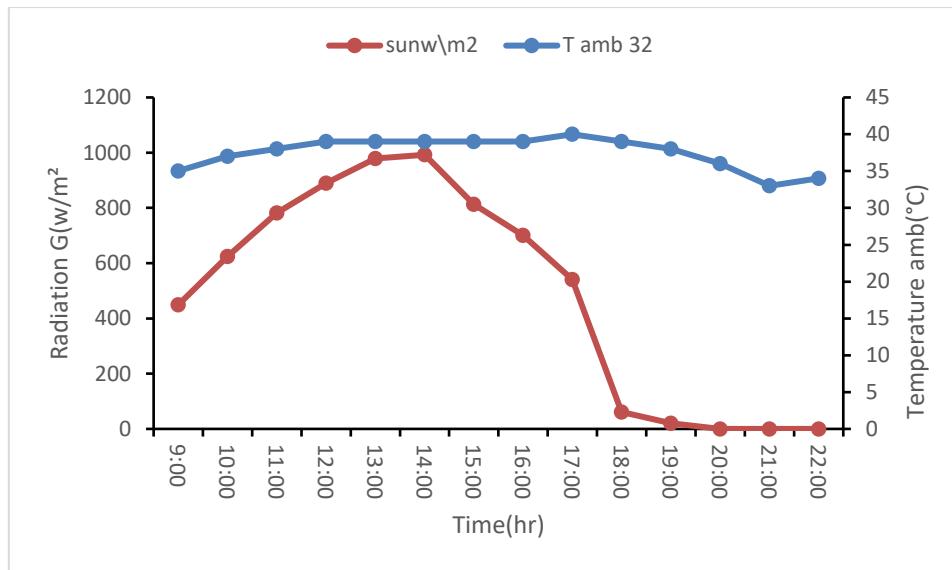
**Figure III.49:** Evolution of the internal temperature of the dryers (with and without) during the days from 18/05/2025

### III.4 Indirect solar drying with paraffin:

This indirect drying method is used with the addition of paraffin—a phase change substance that absorbs heat by changing its state (from solid to liquid or vice versa).

#### III.4.1 Evolution of Solar Radiation and Ambient Temperature (20/05/2025)

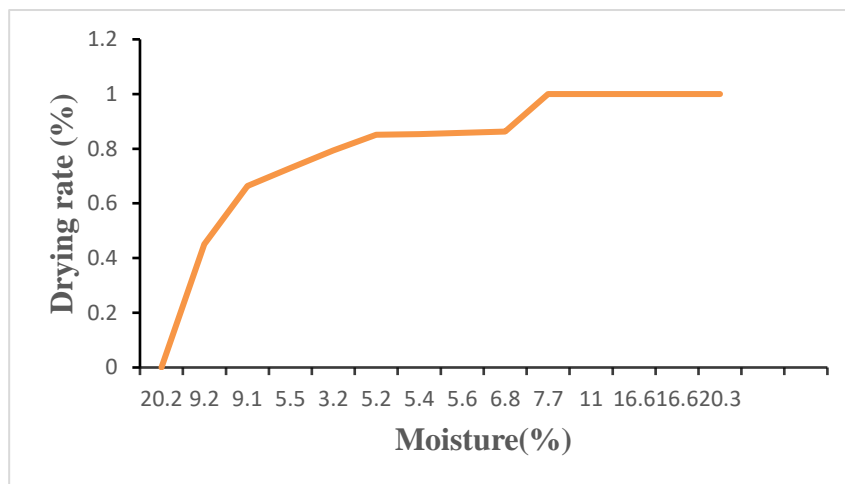
The graph illustrates the progression of solar radiation ( $\text{W/m}^2$ ) and ambient temperature (T1) throughout the day. Solar radiation steadily rises from morning, peaks around midday, and then gradually declines in the afternoon. The ambient temperature follows a similar trajectory, reaching its highest point during midday hours. The inclusion of paraffin as thermal mass aids in stabilizing temperature fluctuations by absorbing and storing heat, helping to maintain more consistent conditions. This trend highlights that the drying process is most efficient when solar radiation is at its peak, while cooling in the afternoon may necessitate additional heat storage mechanisms to sustain drying efficiency.



**Figure III. 50:** Recorded daily solar radiation and ambient temperature evolution

**III.4.2 Drying Rate as a Function of Moisture Content (20/05/2025)**

The drying rate increases significantly as moisture content decreases, a typical characteristic of drying processes. Initially, when moisture content is high, drying occurs rapidly, marked by a steep rise in the drying rate. As the material dries further, the rate of moisture removal gradually slows, demonstrating the diminishing efficiency of evaporation. The curve’s leveling off at lower moisture levels suggests that continued drying will require additional time or energy input to reach the material’s equilibrium moisture content.

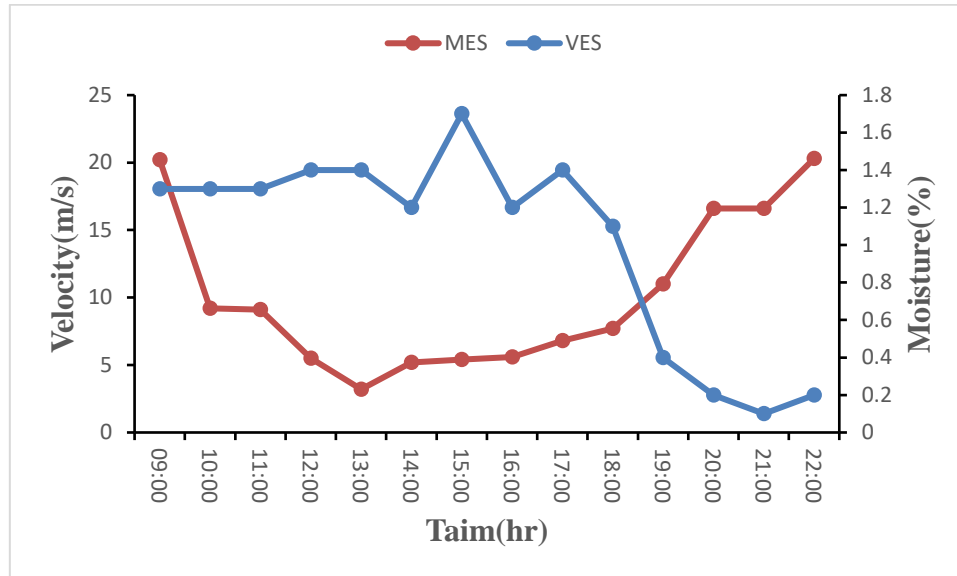


**Figure III.51:** Evolution of drying rate as a function of water content of lemon

**III.4.3 Evolution of Moisture and Air Velocity in the Solar Dryer (20/05/2025)**

This graph illustrates the inverse correlation between moisture content (MES) and air velocity (VES) throughout the drying process. As air velocity increases, moisture content decreases, a typical trend in drying operations where enhanced airflow accelerates moisture evaporation. The fluctuations in both parameters throughout the day highlight the dynamic nature of the

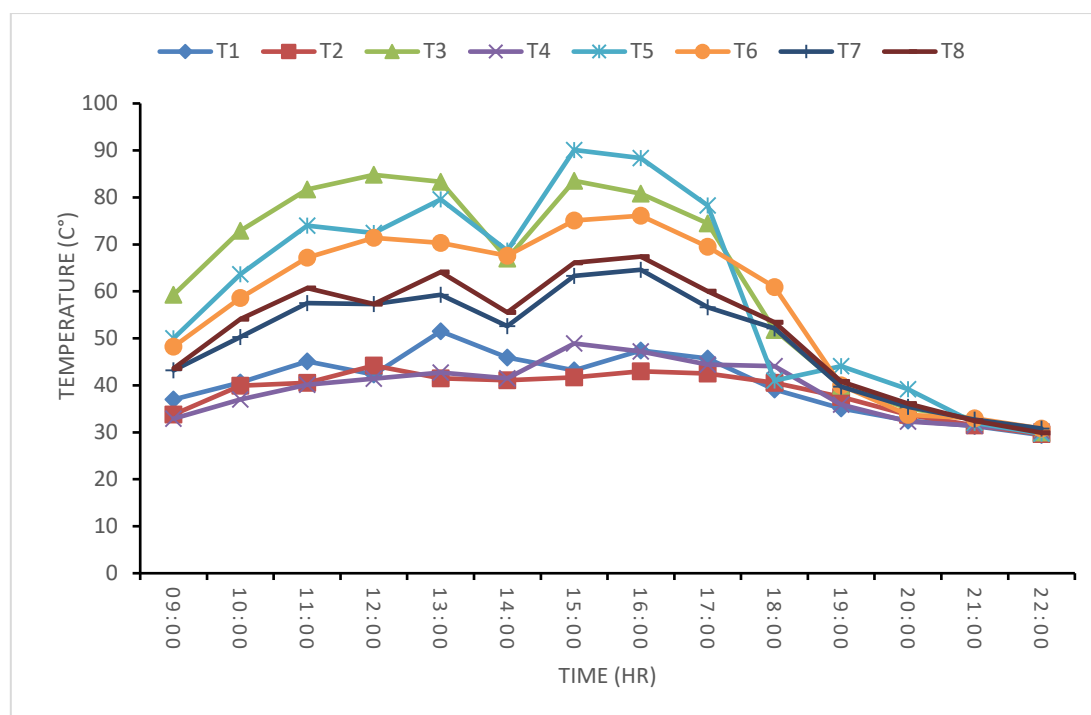
drying process, likely influenced by variations in sunlight intensity and environmental conditions. The peaks in air velocity around midday coincide with lower moisture content, underscoring the efficiency of drying during periods of peak solar radiation.



**Figure III.52 :** Evolution of moisture and air velocity of the solar dryer during the drying of lemon 20/05/2025

#### III.4.4 Evolution of Internal Temperature in the Dryers (20/05/2025)

The internal temperature profile of the dryer follows an expected upward trend throughout the day, reaching its peak around midday when solar radiation is at its highest. The temperature variations across different points (T1 to T8) reveal a thermal gradient within the dryer, with the highest temperatures recorded near the heat source (T1, T2) and lower temperatures at more distant points (T7, T8). This uneven heat distribution may lead to inconsistencies in drying performance, suggesting that optimizing heat dispersion could improve overall drying efficiency and uniformity.



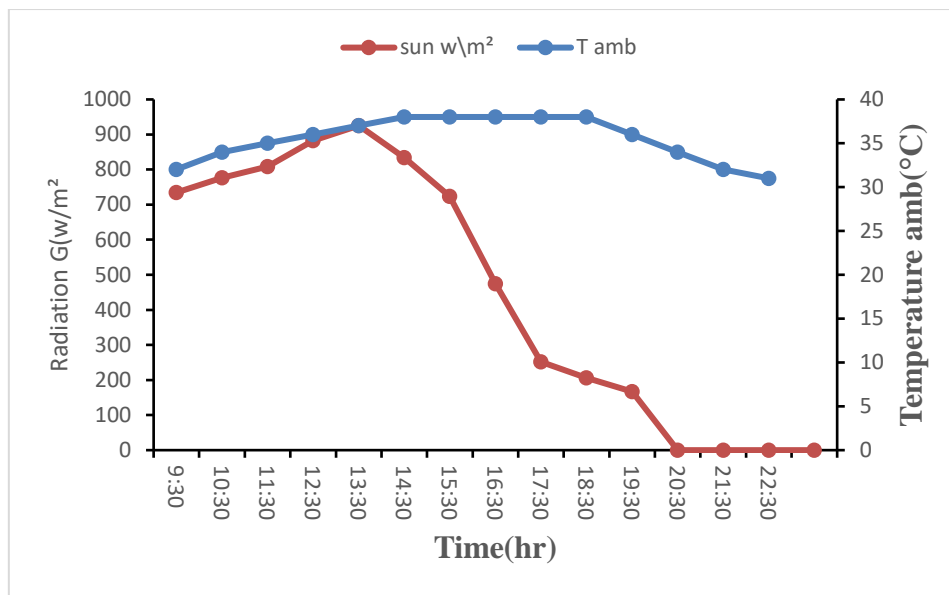
**Figure III. 53:** Evolution of the internal temperature of the dryers (with and without) during the days from 20/05/2025

### III.5 Indirect solar drying with paraffin with a fan:

This method combines indirect drying, paraffin, and an air extractor to enhance drying efficiency by stabilizing the temperature and improving air circulation.

#### III.5.1 Evolution of Solar Radiation and Ambient Temperature (19/05/2025)

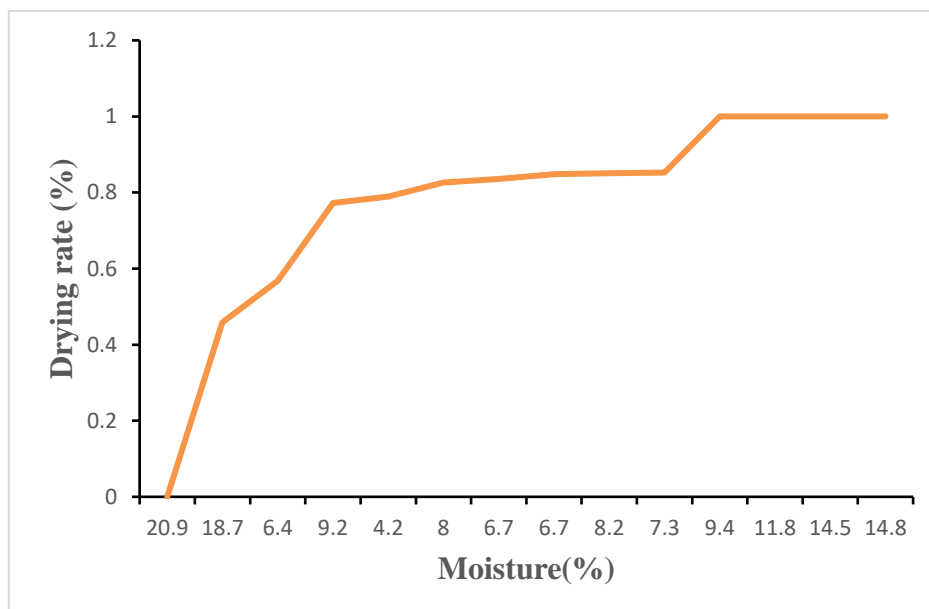
The graph illustrates the progression of solar radiation ( $\text{W}/\text{m}^2$ ) and ambient temperature (T1) throughout the day. Solar radiation rises from morning, reaches its peak around noon, and then gradually declines in the afternoon. Ambient temperature follows a similar pattern, increasing with higher solar radiation and decreasing as sunlight fades. The temperature drop after peak solar radiation suggests that, without an additional heat source, drying efficiency would diminish later in the day. Integrating paraffin as thermal mass along with air extractors can help stabilize temperatures and enhance drying performance during the cooling phase in the afternoon.



**Figure III.54:** Recorded daily solar radiation and ambient temperature evolution

### III.5.2 Drying Rate as a Function of Moisture Content (19/05/2025)

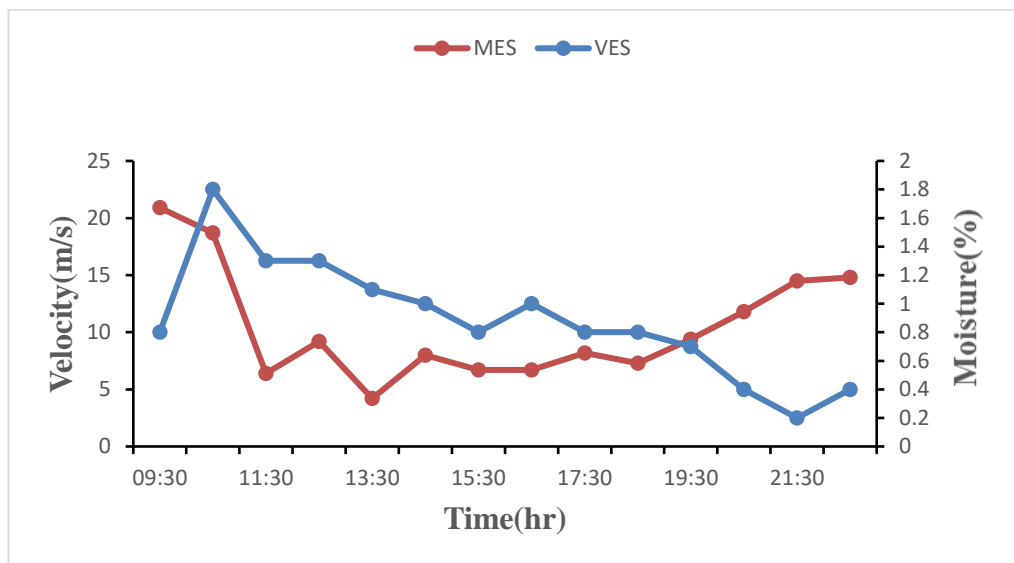
The drying rate increases significantly as moisture content decreases, a typical characteristic of drying processes. Initially, when moisture content is high, the drying rate rises steeply due to rapid moisture evaporation. As the material dries further, the rate of moisture removal slows, reflecting reduced drying efficiency. The leveling off of the drying rate at lower moisture levels indicates that continued drying requires additional time or energy as the material approaches its equilibrium moisture content.



**Figure III. 55:** Evolution of drying rate as a function of water content of lemon

### III.5.3 Evolution of Moisture and Air Velocity in the Solar Dryer (19/05/2025)

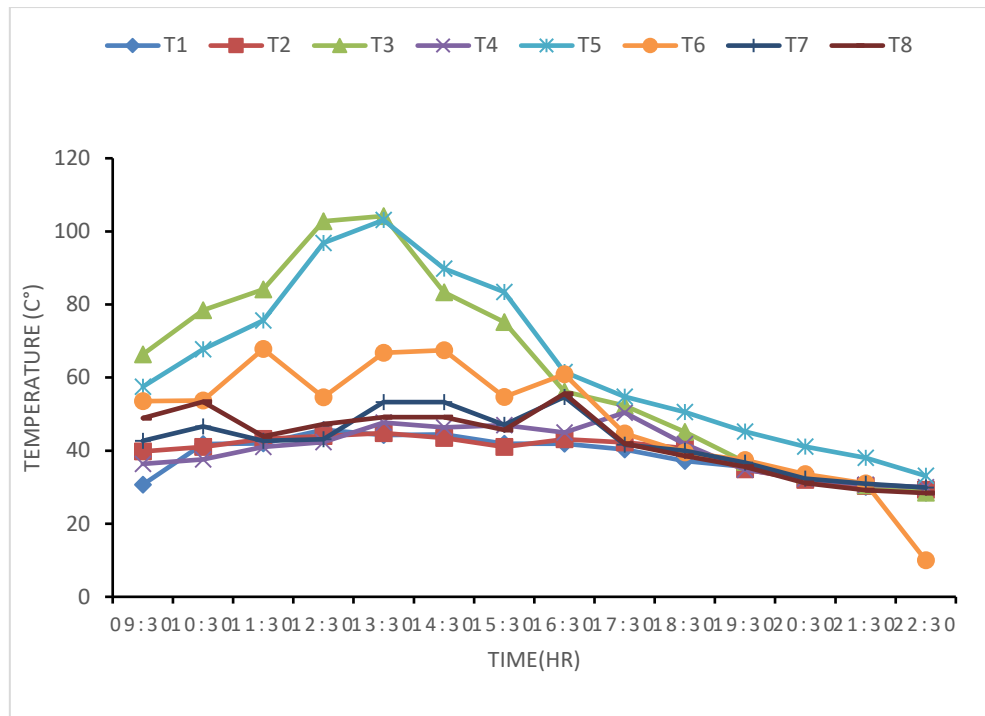
This graph illustrates the inverse relationship between moisture content (MES) and air velocity (VES). As air velocity increases, moisture content decreases, demonstrating the role of airflow in enhancing evaporation. The fluctuations in both parameters throughout the day highlight the dynamic nature of the drying process, which is influenced by factors such as sunlight intensity, airflow variations, and environmental conditions. The graph suggests that drying efficiency is highest when air velocity peaks around midday, coinciding with maximum solar radiation.



**Figure III.56:** Evolution of moisture and air velocity of the solar dryer during the drying of lemon 19/05/2025

### III.5.4 Evolution of Internal Temperature in the Dryers (19/05/2025)

The temperature curve reflects the internal temperature variations within the dryer, with the highest values occurring around midday when solar radiation reaches its peak. Higher temperatures are observed at points closer to the heat source (T1, T2), while points farther away (T7, T8) register lower temperatures, indicating thermal gradients within the drying chamber. These temperature differences suggest uneven heat distribution, which could result in inconsistent drying. Optimizing heat dispersion across the dryer may enhance drying efficiency and ensure uniform moisture removal.



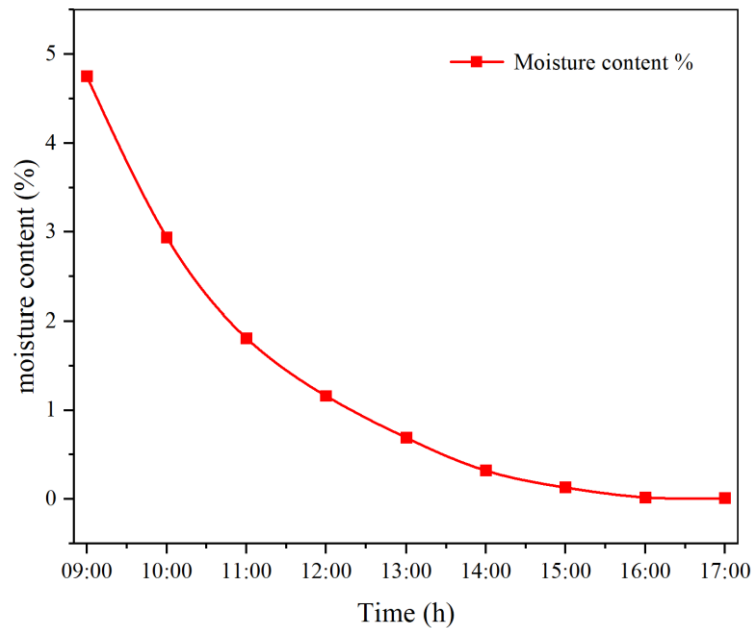
**Figure III.57:** Evolution of the internal temperature of the dryers (with and without) during the days from 19/05/2025

### III.6 The first case result:

#### Solar Drying Curves – Lemon Slices (06/05/2025)

##### 1. Moisture Content

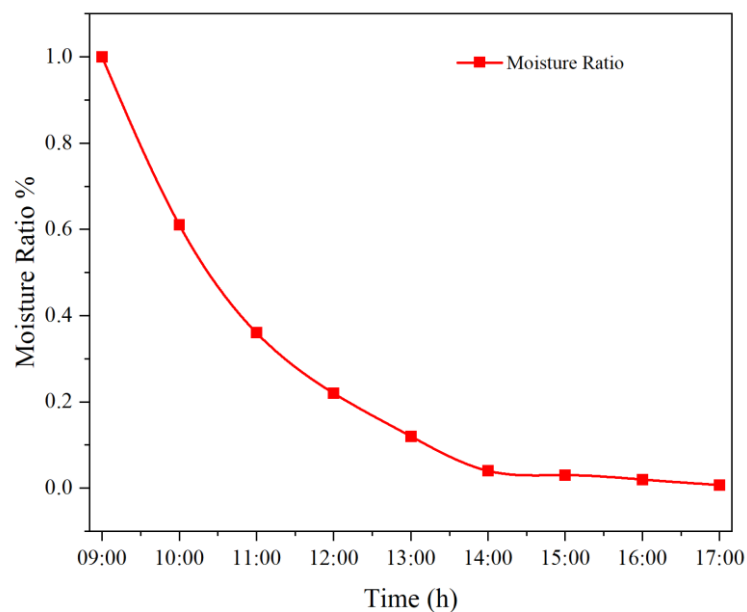
This curve shows the decrease in dry basis moisture content (MC) of lemon slices from approximately 4.75% to 0.01% between 09:00 and 17:00. The sharp decline in the early hours indicates rapid evaporation of surface moisture due to high solar radiation. As time progresses, the curve becomes less steep, signifying a slower drying process governed by internal moisture diffusion during the falling rate phase.



**Figure 58:** Variation of moisture content as a function of time for without fan speed.

## 2. Moisture Ratio

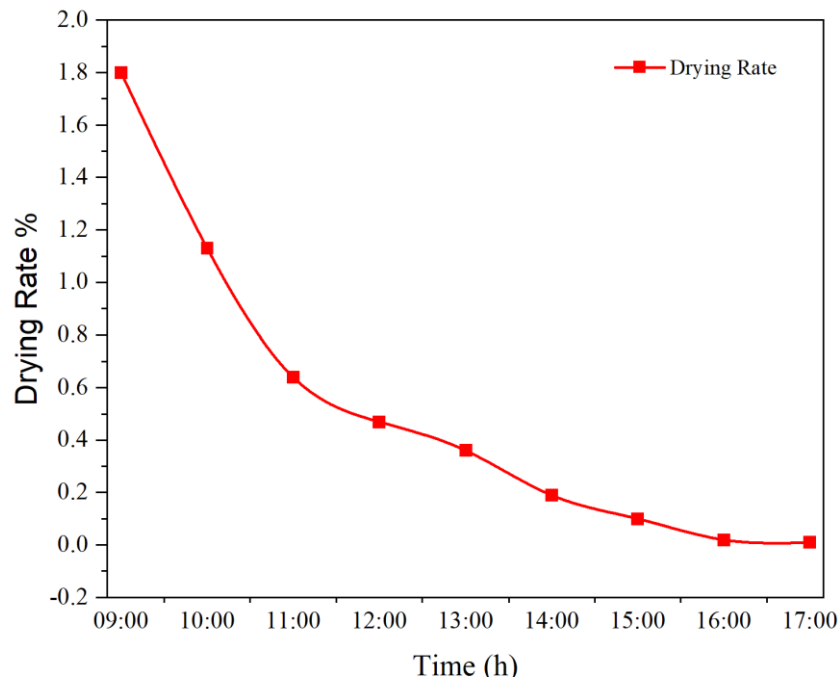
This curve illustrates the decline in the Moisture Ratio (MR) over time. Initially, the MR drops sharply due to a high moisture gradient and efficient surface drying. Later, the decline slows down, reflecting the difficulty in removing moisture from the inner structure of the lemon slices as they near complete dryness.



**Figure 59:** Variation of moisture Ratio as a function of time for without fan speed.

### Drying Rate

The drying rate curve indicates the highest rate at the beginning (around 1.8 % at 09:00), corresponding to the rapid surface moisture loss. As drying continues, the rate decreases due to a reduction in free moisture, and drying becomes more dependent on internal moisture diffusion.



**Figure 60:** Variation of drying rate as a function of time for without fan speed.

### Thermal Efficiency

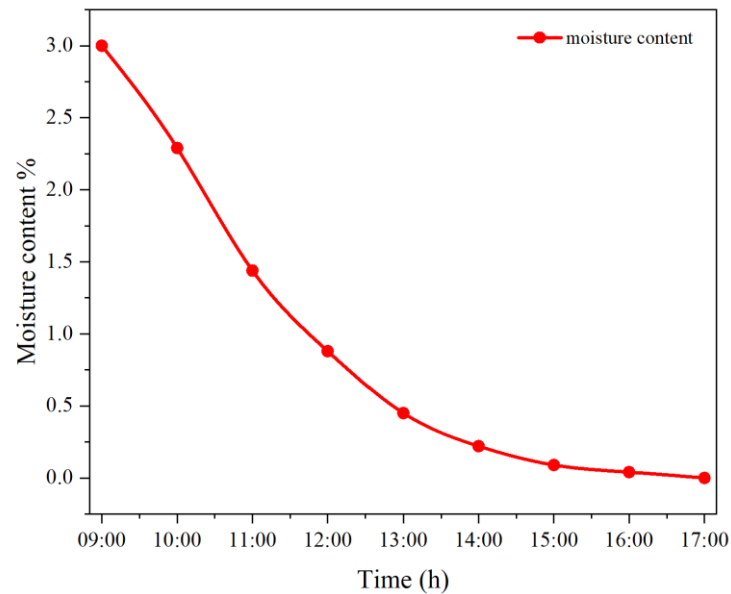
Thermal efficiency initially peaks at 45.4% at 09:00, then drops and fluctuates throughout the day, with values ranging from 18.07% to 35.5%. These fluctuations are likely due to variations in solar intensity and changing moisture content. The efficiency improves slightly in the afternoon before settling at 26.28% by 17:00, indicating better utilization of available solar energy during stable environmental conditions.

### III.7 The second case result:

#### Solar Drying Curves – Lemon Slices (18/05/2025)

##### 1. Moisture content

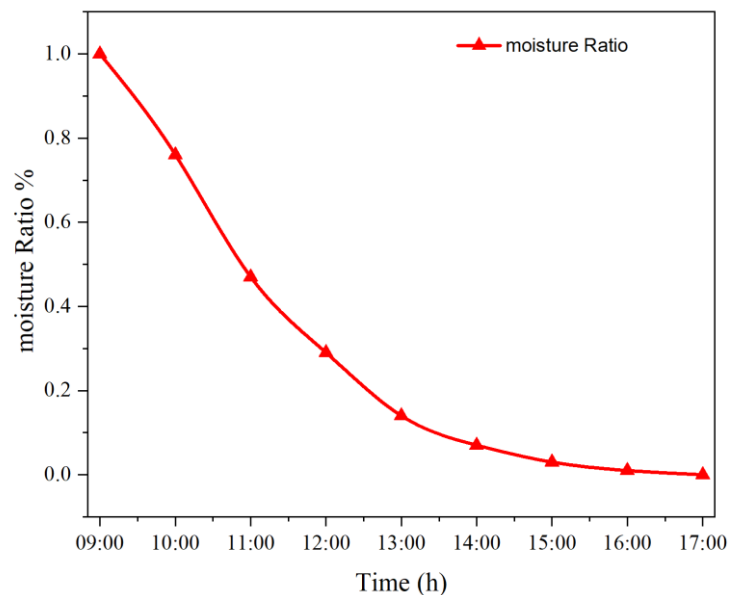
This curve shows the decrease in dry basis moisture content (MC) of lemon slices from approximately 5.8% to 0.0% between 09:00 and 17:00. The steep decline at the beginning reflects rapid surface moisture evaporation under high solar radiation. As time progresses, the curve flattens, indicating slower internal moisture diffusion, marking the transition to the falling rate drying phase.



**Figure 61:** Variation of moisture ratio as a function of time for with fan speed.

## 2. Moisture Ratio

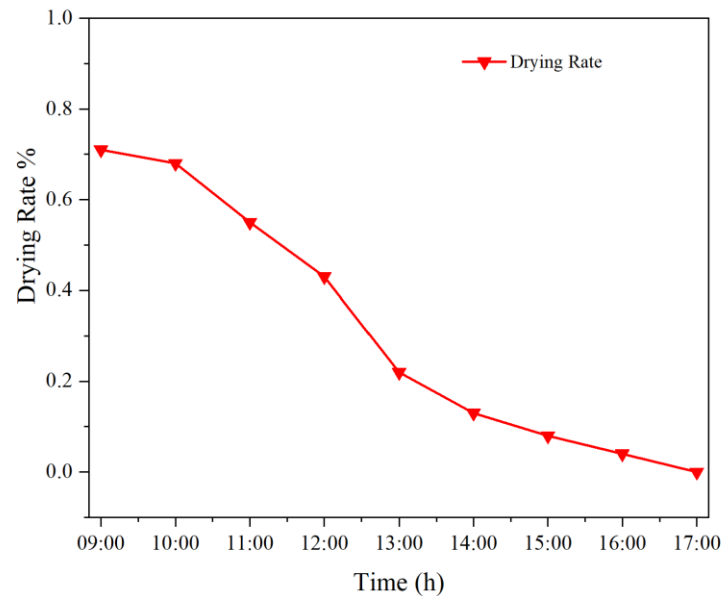
This curve demonstrates a continuous decrease in the Moisture Ratio (MR) throughout the drying process. Initially, MR drops sharply due to high moisture gradients and surface water loss. Later, it decreases more slowly, indicating that internal moisture migration becomes the limiting factor as the lemon slices approach dryness.



**Figure 62:** Variation of moisture Ratio as a function of time for with fan speed

### 3. Drying Rate

The drying rate is highest at the start (about 3 % at 09:00), reflecting intense evaporation of surface moisture. It then decreases significantly as internal moisture becomes harder to remove. The steady decline after 12:00 indicates that internal diffusion governs the drying process during the later phase.



**Figure 63:** Variation of drying rate as a function of time for with fan speed.

### 4. Thermal Efficiency

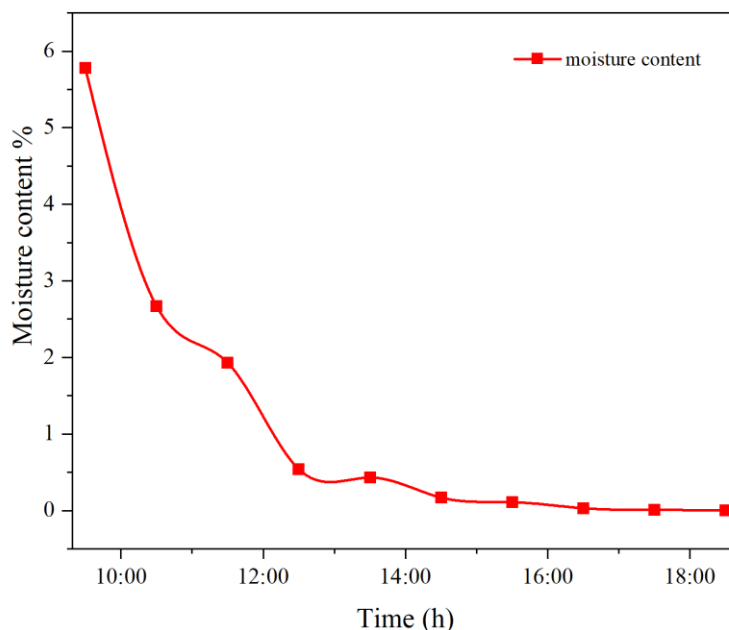
Thermal efficiency increases sharply from 17.65% at 09:00 to a peak of 54.26% around noon, then declines to 22.49% by 17:00. This trend reflects optimal solar energy utilization in the first half of the day and a decline due to lower solar intensity and moisture availability in the afternoon.

#### III.8 The Third Case result:

##### Solar Drying Curves Lemon Slices (20/05/2025)

#### 1. moisture content

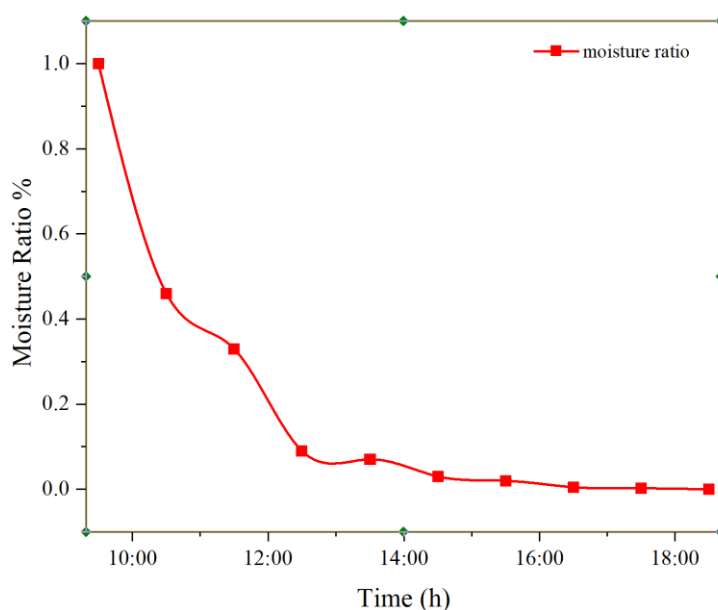
This curve illustrates the reduction in moisture content on a dry basis (MC) of lemon slices from approximately 6.2% to nearly 0% between 11:00 and 19:00. The sharp initial drop indicates rapid surface water evaporation due to intense solar radiation. As the drying process continues, the slope flattens, signaling a shift to internal moisture diffusion dominance the falling rate period.



**Figure 64:** Variation of moisture content as a function of time for with paraffin and fan speed.

### Moisture Ratio

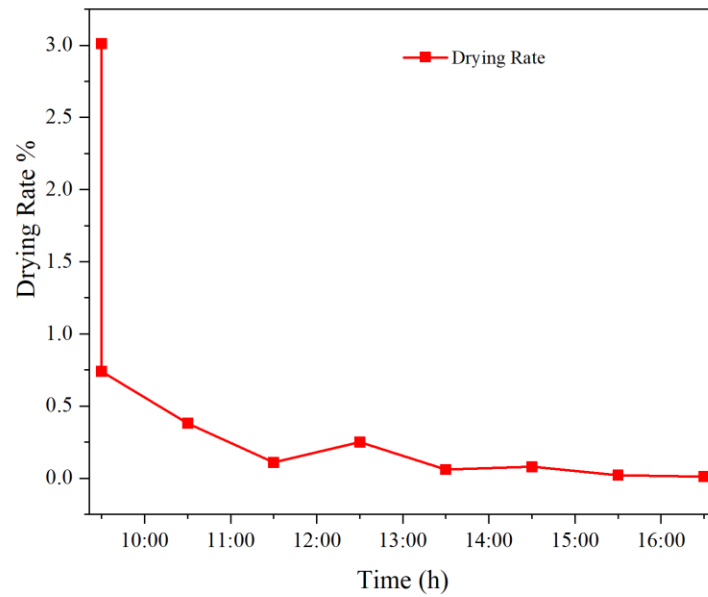
The moisture ratio (MR) decreased consistently throughout the drying process. A steep initial drop reflects effective moisture removal at the surface. As drying progresses, the rate of decrease slows, showing that internal moisture diffusion limits the drying speed in the later stages.



**Figure 65:** Variation of moisture rate as a function of time for with paraffin and fan speed.

## 2. Drying Rate

The drying rate reached a peak of around 3.2 % at 11:00, then declined sharply. This drop is due to the depletion of easily removable surface moisture. After 13:00, the drying rate stabilized at very low levels, confirming the dominance of the falling rate period governed by internal diffusion.



**Figure 66:** Variation of drying rate as a function of time for with paraffin and fan speed.

### 3. Thermal Efficiency

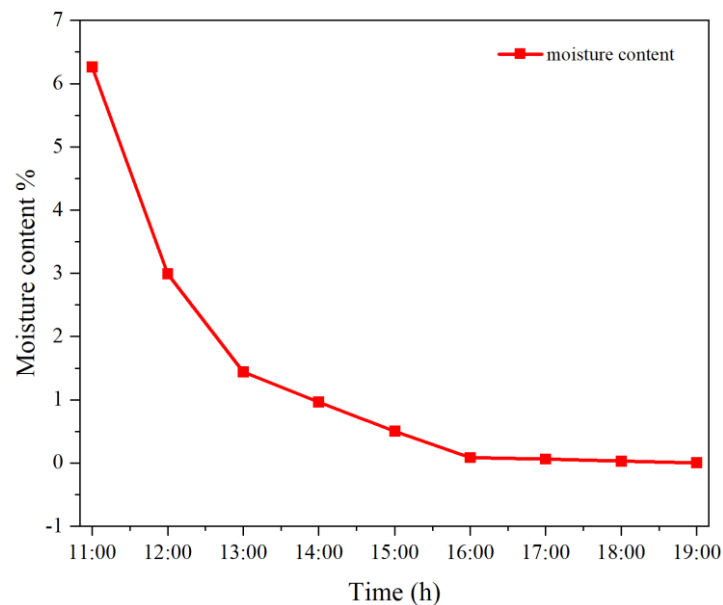
Thermal efficiency increased to a peak of nearly 40% around midday, then fluctuated throughout the afternoon. This trend reflects changes in solar intensity, ambient temperature, and moisture content in the slices. The final drop in efficiency after 17:00 indicates lower solar input and reduced drying potential toward the end of the session.

### III.9 The fourth case result:

#### Solar Drying Curves – Lemon Slices (19/05/2025)

##### 1. Moisture Content

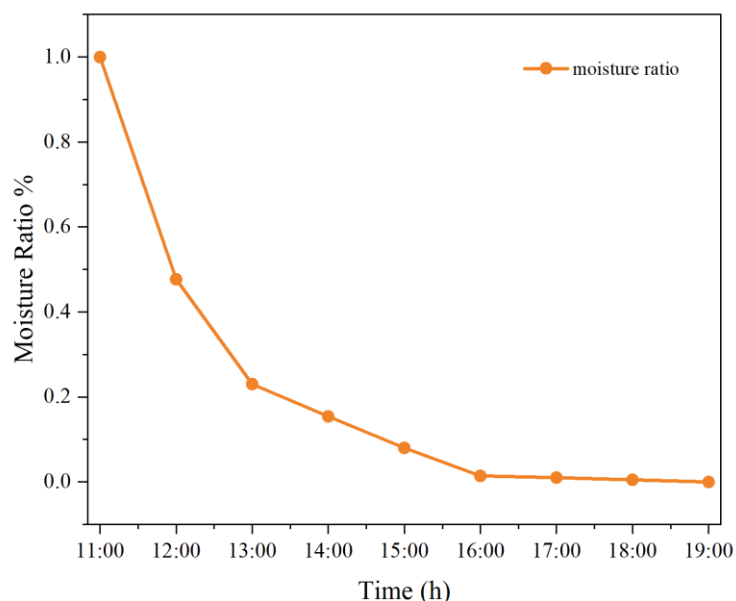
This curve represents the variation of moisture content on a dry basis (MC) over time. The MC decreased from approximately 5.9% at 09:00 to nearly 0.0% at 18:00. The sharp decline during the first few hours indicates rapid evaporation of surface moisture due to high solar energy input. As the slices dried, the rate of moisture loss slowed down, marking the transition from the constant rate period to the falling rate period where internal moisture diffusion becomes the limiting factor.



**Figure 67:** Variation of moisture content as a function of time for with PCM.

##### 2. Moisture Ratio

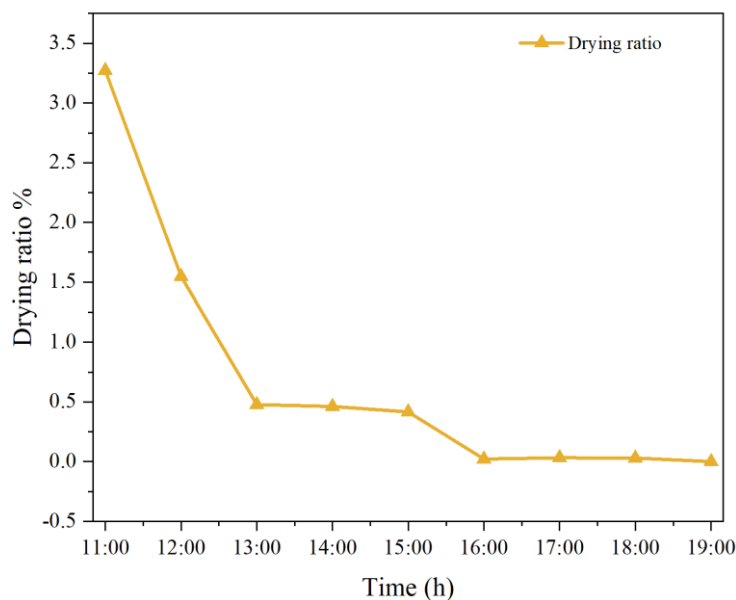
The moisture ratio decreased consistently throughout the drying period, starting from 1.0 and reaching almost zero by the end of the day. The initial sharp drop reflects high moisture gradients that drive fast moisture removal from the lemon slices. As the drying progresses, the gradient weakens, and the curve flattens, confirming a shift to internal moisture transport control.



**Figure 68:** Variation of moisture ratio as a function of time for with PCM.

### 3. Drying Rate

The drying rate started at approximately 3.0 % at 09:00 and decreased progressively to near 0.0 % by 17:00. This trend highlights an intense initial drying phase followed by a prolonged falling rate period. The temporary slight increase around 13:00 may be due to transient improvements in airflow or radiation intensity.



**Figure 69:** Variation of drying ratio as a function of time for with PCM.

### 4. Thermal Efficiency ( $\eta$ ) vs Time

Thermal efficiency ( $\eta$ ) started at around 18%, peaked at approximately 50% by midday, and then gradually declined to about 8% by the end of the drying session. This indicates that solar energy was most effectively utilized

during the central hours of the day when both solar intensity and internal product moisture were optimal. The decrease after 15:00 reflects reduced solar input and limited available moisture for evaporation.

**Conclusion:**

This study on the efficiency of various solar drying techniques for lemon slices demonstrates the significant potential of solar energy in enhancing food preservation while being energy-efficient and environmentally friendly. The results obtained from the different methods of indirect solar drying, including the use of paraffin, fans, and their combinations, provide valuable insights into optimizing drying systems.

- Conventional indirect solar drying proved effective in utilizing solar radiation for moisture removal, but it highlighted the need for better heat distribution within the dryer to ensure uniform drying.
- Indirect solar drying with paraffin demonstrated the benefits of using phase change materials to stabilize temperature fluctuations, particularly during the afternoon when solar radiation decreases. This method enhanced drying efficiency by providing a more consistent heat environment.
- Indirect solar drying with a fan improved drying performance by increasing airflow, leading to enhanced moisture removal, especially during midday when solar radiation and airflow reached their peak.
- The combination of paraffin and a fan-assisted system showed the best results by stabilizing temperature variations and optimizing airflow dynamics, leading to more efficient drying and improved moisture removal.

Key parameters such as solar radiation, ambient temperature, drying rate, moisture content, air velocity, and internal temperature were critical in assessing the drying process. It is clear that optimizing these factors can significantly enhance drying efficiency and ensure consistent results.

In conclusion, integrating phase change materials like paraffin, improving airflow with fans, and optimizing drying techniques can significantly improve solar drying systems. These methods not only enhance energy efficiency but also provide an effective solution for preserving agricultural products in a sustainable manner. Future research could further explore combining these techniques with other innovative strategies to improve solar drying performance for a broader range of products.

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## General Conclusion:

This dissertation presents a comprehensive study on the performance of an indirect solar dryer enhanced with thermal energy storage and a heat recovery system. The aim was to assess its practicality, benefits, and limitations as a sustainable solution for drying agricultural products. Through detailed evaluation, several critical findings were obtained that highlight the system's potential impact and future relevance.

To this end, four experimental trials were conducted to evaluate the influence of different technical modifications on the drying performance of lemon slices:

Test 1 – Baseline (Natural Convection): The dryer operated without any mechanical aid, relying solely on natural airflow through the system.

Test 2 – Solar-Powered Fan: A DC fan powered by a solar panel was added to enhance airflow and improve the drying rate through forced convection.

Test 3 – Fan + Solar Panel + Paraffin PCM: The system was further improved by integrating both the solar-powered fan and paraffin-based Phase Change Material (PCM). The PCM stored excess heat during the day and released it during periods of low radiation, allowing continuous drying and thermal stability.

Test 4 – No Fan, No Solar Panel (Post-PCM Charging): This trial removed both the fan and the solar panel, relying solely on the previously charged PCM to assess its capacity to maintain thermal performance independently.

These four configurations allowed for a comparative analysis of thermal performance, drying rate, and moisture removal efficiency. Notably, Test 3 demonstrated superior results, combining extended drying time and energy efficiency due to PCM's thermal buffering and forced convection. All experiments were conducted under real climatic conditions at the Faculty of Materials Science, Kasdi Merbah University, Ouargla. The dryer with the heat recovery system achieved an average air temperature of 35°C and absorber plate temperature of 65°C, while the conventional dryer without the system reached 65°C and 112°C respectively. Using lemon slices as the target product, the initial moisture content decreased from 93% to 11% within three to four days. The setup in Test 3 reduced the drying time by about one day and improved internal temperature control by nearly 20°C, equivalent to an efficiency gain of approximately 30%. Given the thermal performance of the improved system, it is recommended to integrate PCM containers into the final dryer design to maintain consistent drying conditions during low radiation periods or nighttime.

Although the weather conditions during the experimental period were not always ideal, and further tests were limited by time constraints, this study clearly demonstrates the potential of combining indirect solar drying, heat recovery, and thermal energy storage as an integrated, efficient, and sustainable solution for food preservation. In conclusion, the developed dryer system offers a promising path for energy-efficient, environmentally friendly, and cost-effective agricultural drying, paving the way for future innovations in solar thermal applications.

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