People`s Democratic Republic of Algeria

Ministry of Higher Education and Scientific Research

University of Echahid Hamma Lakhdar - El Oued

Faculty of Technology

Department of Mechanical Engineering Dissertation

ACADEMIC MASTER

Domain: **Science and Technology**

Division: **Mechanical Engineering**

Specialty: **Renewable energies**

Presented by:

1. **BERCHAOUA Bachir**
2. **REDOUANI Hamza**

Entitled:

Thermal Enhancement of a Greenhouse Dryer Using a Heat Recovery System

Dissertation Submitted in Partial Fulfillment of the Requirements for the Master

MER

Degree in ………...

Publicly defended in: 14/06/2026

Board of Examiners:

Dr. BENHAMZA Abderrahman	**Chairman**
Dr. ZINE Ali	**Supervisor**
Dr. AOUN Yacine	**Examiner**

Academic Year: 2025/2026

Dedication

This work is wholeheartedly dedicated to:
My beloved parents, for their endless sacrifices, faith in my abilities, and lifelong support.
My brilliant colleague and partner in this journey, for their unwavering commitment, shared hard work, and exceptional collaboration.
My siblings, family, and everyone who believes that knowledge is a weapon against darkness and a beacon for insight.

BERCHAOUA Bachir

Dedication

To those who believed in me before I believed in myself,
This milestone is as much yours as it is mine.
To my family, your endless love was my anchor in every storm.
To my friends, your laughter made the hardest days lighter.
I dedicate this success to the late nights, the tears, and the hope.
Thank you for walking beside me on this beautiful journey.
Here is to the future we will build with the knowledge we gained.

REDOUANI Hamza

Acknowledgements

I would like to express my deepest gratitude and sincere appreciation to my esteemed supervisor, **Dr. Ali Zin**, for his invaluable guidance, continuous support, and profound expertise throughout the development of this work. His insightful directions, constructive criticism, and unwavering encouragement were fundamental in shaping this research and steering it toward success. I am truly privileged to have worked under his supervision.

My profound thanks also go to **Dr. Abdeljalil Laouini** for his constant support and assistance during the experimental phase at the Renewable Energy Research Unit. His technical expertise, availability, and dedication provided a highly stimulating environment that greatly facilitated the successful execution of our experiments.

I am equally grateful to **Dr. Abderrahmane Benhamza** for his invaluable advice, scientific insights, and precise recommendations throughout the experimental period. His thoughtful remarks and guidance significantly contributed to refining our methodology and improving the overall quality of this study.

Finally, I would like to extend my appreciation to all the members, researchers, and technical staff at the Renewable Energy Research Unit for their cooperation and for providing the necessary facilities to conduct this research in the best possible conditions.

Abstract

This work presents the thermal enhancement of an indirect greenhouse solar dryer by integrating a heat recovery system. The experimental study was conducted at the Research and Development Unit for Renewable Energies in Arid Zones (URERMS). The proposed system recovers part of the heat contained in the exhaust air and reuses it to improve the drying process. Cantaloupe (Cucumis melo) was selected as the drying product. Experimental tests were carried out to evaluate the thermal performance of the developed dryer. The results showed that the heat recovery system increased the drying air temperature, reduced thermal losses, and improved the overall drying performance. Consequently, higher drying rates and better utilization of solar energy were achieved. The study demonstrates that integrating a heat recovery system is an effective approach to improving the efficiency of greenhouse solar dryers operating under arid climatic conditions.

Keywords: Solar drying, Greenhouse dryer, Hybrid drying system, Heat recovery, Thermal energy storage, Exergy analysis, Agricultural products, Renewable energy, Drying kinetics

Résumé

Cette étude s'inscrit dans le cadre de la valorisation de l'énergie solaire à travers le développement de technologies durables dédiées à la conservation des produits agricoles périssables et à la réduction des pertes post-récolte. Les recherches se focalisent sur l'optimisation de la conception d'un séchoir solaire de type serre, intégrant un système de ventilation forcée couplé à une technologie innovante de récupération de la chaleur de l'air extrait.

L'expérimentation a été menée au sein de la station d'essais de l'Unité de Recherche en Énergies Renouvelables. Des tranches de melon ont été utilisées comme produit test afin d'évaluer les performances globales du système et d'analyser la cinétique des transferts de masse et de chaleur.

Sur le plan de l'ingénierie thermique, cette étude revêt une importance majeure. En effet, les séchoirs conventionnels subissent des pertes calorifiques considérables dues à l'évacuation continue de l'air chaud. Pour y remédier, un dispositif de récupération thermique a été conçu pour capter cet air chaud et le recirculer en le mélangeant à de l'air neuf, réduisant ainsi la charge thermique requise.

Les résultats expérimentaux ont démontré la haute efficacité du système, caractérisée par l'obtention de températures élevées au niveau du capteur absorbeur. Cela a permis d'élever la température de l'air au sein de la chambre de séchage, créant ainsi un environnement optimal pour la déshydratation des denrées alimentaires thermosensibles.

De plus, l'étude de la cinétique de séchage du melon, basée sur le suivi régulier de la diminution de sa teneur en eau au cours du temps, a été confrontée à différents modèles mathématiques. Il en ressort que le modèle de Midilli-Kucuk s'est avéré le plus précis pour décrire fidèlement le comportement du processus de séchage.

En conclusion, ces travaux mettent en évidence l'intérêt majeur d'intégrer des techniques de récupération de chaleur et de recyclage d'air dans les séchoirs solaires. Cette approche constitue une solution d'ingénierie prometteuse, durable et rentable, permettant d'optimiser l'efficacité énergétique globale du système et d'accélérer les taux de désorption de l'humidité tout en préservant la qualité intrinsèque du produit final.

الملخص

هذه الدراسة تهتم بتعزيز قيمة الطاقة الشمسية من خلال تطوير تقنيات مستدامة لحماية المنتجات الفلاحية التي تتعرض للتلف بسرعة وتقليل الخسائر بعد الحصاد. يركز البحث على تحسين تصميم مجفف البيت الدفيئة الشمسي، والذي يدمج نظام تهوية قسري ويتوفر على تقنية حديثة لاستعادة الحرارة من الهواء العادم.

تم إجراء هذه الدراسة التطبيقية في محطة التجارب التابعة لوحدة البحث في الطاقات المتجددة، حيث تم اختبار شرائح الشمام لتقيم أداء المنظومة ودراسة حركية انتقال الكتلة والحرارة.

هذه الدراسة لها أهمية كبيرة من الناحية الهندسية، لأن المجففات التقليدية تعاني من خسائر كبيرة في الطاقة الحرارية بسبب التخلص المستمر من الهواء الساخن. لذلك، تم تصميم نظام لاستعادة الحرارة، الذي يعمل على التقاط الهواء الساخن وإعادة خلطه مع الهواء النقي، مما يقلل من الجهد الحراري المطلوب.

أظهرت النتائج كفاءة عالية للمنظومة، حيث تم تحقيق درجات حرارة عالية للوحة الامتصاص، وهذا أدى إلى رفع درجة حرارة الهواء في غرفة التجفيف، مما يخلق بيئة مثالية لتجفيف المواد الغذائية الحساسة للحرارة.

كما تمت دراسة حركية التجفيف للشمام، حيث تم تتبع انخفاض المحتوى المائي على فترات زمنية منتظمة، وتمت المقارنة مع نماذج رياضية مختلفة، وتم اكتشاف أن نموذج "ميديللي-كوتشوك" هو النموذج الأكثر دقة في وصف سلوك آلية تجفيف الشمام.

تؤكد هذه الدراسة على أهمية دمج تقنيات استعادة الحرارة وإعادة تدوير الهواء في المجففات الشمسية، وهو حل هندسي واعد ومستدام واقتصادي لرفع الكفاءة الطاقوية الإجمالية للمنظومة وتسريع معدلات إزالة الرطوبة مع الحفاظ على جودة المنتج النهائي.

Nomenclature

Table 1: Nomenclature of drying parameters

Symbol	Description
X_i	Initial moisture content (dry basis)
X_f	Final moisture content (dry basis)
X_0	Initial moisture content at $t = 0$ (dry basis)
X_t	Moisture content at time t (dry basis)
X_e	Equilibrium moisture content (dry basis)
XR	Moisture ratio
D_{eff}	Effective moisture diffusivity ($m^2\ s^{-1}$)
m_{evap}	Mass of evaporated moisture (kg)
L	Half thickness of product slice (m)
t	Drying time (s, min, or h)

Table of Contents

List of Figures

List of Tables

1 General Introduction

The contemporary global energy landscape faces a critical challenge that necessitates an inevitable transition toward renewable energy sources as a fundamental pillar for mitigating climate change and reducing greenhouse gas emissions, particularly carbon dioxide generated from the combustion of fossil fuels. Among the available renewable technologies, solar thermal systems have emerged as one of the most efficient and sustainable solutions for industrial and agricultural applications. Drying, in particular, constitutes a strategic operation in food engineering, as it reduces water activity and moisture content in agricultural products, thereby inhibiting microbial growth and enzymatic reactions responsible for deterioration.

However, conventional open-sun drying techniques suffer from several inherent limitations, including the inability to control operating parameters, direct exposure to ultraviolet radiation that degrades product quality, and contamination from external pollutants. Conversely, forced-convection drying systems powered by conventional energy sources consume substantial amounts of fossil fuels. In this context, greenhouse solar dryers have attracted considerable attention as promising engineering solutions; nevertheless, their thermal performance remains strongly dependent on solar radiation fluctuations and is often constrained during nighttime periods.

This challenge is particularly evident in the Saharan climate of El Oued Province (southeastern Algeria). Despite possessing exceptional solar resources exceeding 6.25 $kWh\ m^{-2}\ day^{-1}$, significant quantities of agricultural produce are lost due to the lack of sustainable preservation and drying technologies. Accordingly, the present study focuses on the engineering development and energy performance assessment of an indirect hybrid greenhouse solar dryer integrated with an innovative heat recovery system designed to enhance thermal stability and improve drying efficiency.

The research aims to provide both experimental and theoretical analyses of heat and mass transfer mechanisms within the drying chamber, while also investigating the drying kinetics of agricultural products. To achieve these objectives, the dissertation is organized into three main chapters.

The first chapter reviews relevant previous studies,

The second presents the experimental methodology and mathematical modeling framework,

The third is devoted to the presentation, analysis, and discussion of the obtained results.

Literature Review

Chapter 1

Literature Review

1.1 Introduction

In this first chapter of the study, relevant research related to the topic will be reviewed in order to provide a general overview of solar dryer technologies. The chapter begins with a general classification of these dryers, preparing the reader for a deeper understanding of the various aspects of this field.

The chapter primarily focuses on advancements in solar air collectors and their role in improving the performance of solar drying systems. It highlights key innovations and design improvements that have contributed to enhancing their efficiency and effectiveness. In addition, the chapter addresses improvements applied to drying chambers by reviewing different approaches aimed at enhancing heat transfer and distribution within the drying space.

Through this discussion, the chapter provides a general understanding of the most important previous studies in solar drying technology, while shedding light on areas that still require further research and development. Thus, the role of this chapter is not limited to presenting previous technologies, but also extends to identifying research gaps, thereby paving the way for the subsequent chapters of the thesis.

1.2 Basic Concepts and Theoretical Foundations

1.2.1 Principles of Solar Energy

1.2.1.1 Solar radiation

Solar radiation is defined as the energy emitted by the sun that reaches the Earth's surface in the form of electromagnetic waves. Its intensity is measured in watts per square meter (W/m^2) and is referred to as incident solar radiation, which represents the primary energy source for many thermal applications, particularly solar drying systems. This radiation is composed of three main components: infrared radiation, visible light, and ultraviolet radiation. It spans a wide range of wavelengths, and each component contributes differently to the generation of thermal energy required to increase air and product temperatures within drying systems.

In this context, understanding solar geometry is a key factor in optimizing the design and orientation of solar dryers. It is based on three fundamental angles: the angle of incidence, which describes the angle at which solar rays strike a surface; the zenith angle, which defines the position of the sun relative to the vertical direction; and the azimuth angle, which represents the horizontal direction of incoming solar radiation. These angles continuously change throughout the day and across seasons due to the Earth's rotation and its orbit around the sun, directly affecting the amount of solar energy received and its effective utilization.

To harness this energy efficiently, solar radiation is converted into usable thermal energy through solar collectors. These devices are specifically designed to absorb solar radiation and transform it into heat used for warming air or fluids. Various types of solar collectors exist, including flat-plate collectors, which are widely used due to their simplicity; evacuated tube collectors, which offer higher efficiency by minimizing heat losses; and parabolic collectors, which are typically used in high-temperature applications. The selection of a suitable collector depends on the application requirements and desired performance level, making solar dryer design a multidisciplinary process that integrates radiative, geometrical, and technical considerations to achieve maximum efficiency.

1.2.1.2 Principles of Drying Processes

Drying processes are considered one of the fundamental thermal operations aimed at removing moisture from materials in order to improve their preservation, quality, and stability. These processes are based on a set of physical principles related to heat and mass transfer. Moisture content is defined as the ratio of the amount of water contained in a material to its dry weight and is usually expressed as a percentage. Accurate control of moisture content is essential to ensure a high-quality dried product with stable long-term properties.

The drying rate is typically described by a curve consisting of two main stages. The first stage is the constant rate period, during which surface moisture is removed from the material at a relatively steady rate. This rate is strongly influenced by external conditions such as temperature and air velocity. The second stage is the falling rate period, where the drying rate gradually decreases due to the increasing difficulty of transferring moisture from the interior of the material to its surface, making the process more dependent on the internal properties of the material.

Moisture removal mechanisms are mainly based on two processes: evaporation and diffusion. Evaporation refers to the transformation of liquid water on the material's surface into vapor, which is then carried away by airflow, while diffusion describes the movement of water molecules within the material from regions of higher concentration toward regions of lower concentration until they reach the surface, where evaporation occurs.

The efficiency of the drying process is influenced by several interrelated factors, including temperature, which accelerates evaporation by increasing the kinetic energy of water molecules; relative humidity, where lower humidity enhances the moisture gradient between the material and the surrounding air, thereby speeding up drying; and airflow velocity, which helps remove the generated vapor and prevents saturation around the material. In addition, the physical and chemical properties of the material, such as porosity, internal structure, and hygroscopicity, play a crucial role in determining the drying behavior, rate, and overall efficiency.

1.3 Design and operation of solar dryers

1.3.1 Types of solar drying

Majorly solar crop drying is divided into two categories : open sun drying and crop drying in solar dryer shown in Fig.1.1.

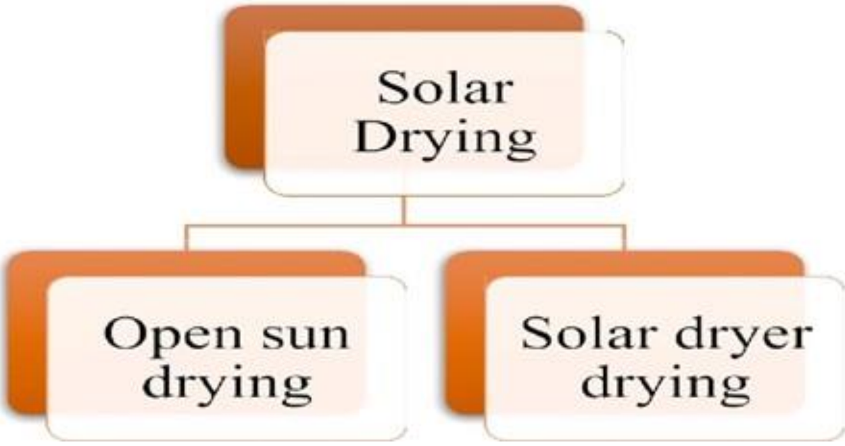

Figure 1.1: Type of solar dryer [1]

1.3.1.1 Open sun drying OSD

The working principle of the OSD shown in Fig.1.2. is based on the interaction between solar radiation and the crop surface. A fraction of the incoming solar radiation falls on the irregular surface of the crop, where part of the energy is reflected while the remaining portion is absorbed. The amount of absorbed energy depends largely on the color and physical characteristics of the crop. As the crop absorbs solar energy, its temperature gradually increases. This rise in temperature promotes heat and mass transfer between the crop surface and the surrounding air, accompanied by convective heat losses and long-wave radiation losses. The intensity of convective heat transfer mainly depends on the airflow velocity passing over the crop surface. Moisture removal occurs through evaporation, which leads to the drying of the crop. At the same time, a portion of the absorbed thermal energy penetrates into the inner layers of the crop by conduction. The increase in internal temperature stimulates the formation of water vapor within the crop material, initiating vapor diffusion toward the outer surface. As moisture evaporates from the surface, the overall mass of the product decreases. Therefore, the efficiency of solar drying is strongly related to the rate at which internal moisture diffuses toward the crop surface, depending on the nature and structure of the product [2,3]. However, open sun drying often results in considerable crop losses due to rodents, birds, insects, unexpected rainfall, and storms. In addition, prolonged exposure to direct sunlight may cause discoloration of the dried products [4].

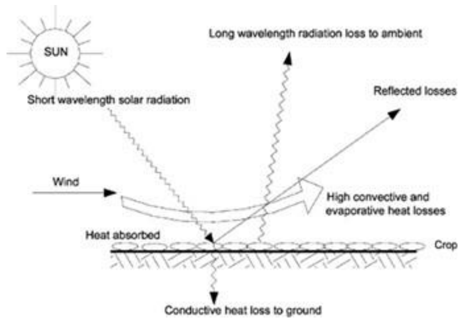

Figure 1.2: Open sun drying[5].

1.3.1.2 Solar dryer drying

To overcome the limitations associated with open sun drying (OSD), agricultural products are dried inside enclosed systems known as solar dryers. Solar dryers, including greenhouse dryers (GHDs), can be classified according to several criteria, such as the mode of heat transfer (direct, indirect, or mixed mode), the mode of air circulation (active or passive), and the roof configuration (single-slope, double-slope, parabolic, or tunnel-shaped structures). Based on the available literature, a broad pictorial classification of solar drying technologies has been presented in Fig.1. 3. Among these classifications, the most important distinction is related to the heat transfer mode—direct, indirect, and mixed-mode drying—because it strongly affects the dryer design, operating efficiency, and suitability for different agricultural products and climatic conditions [6].

In direct-mode solar drying, solar radiation falls directly on both the solar collector and the crop, which is positioned beneath it. Although this arrangement is simple and economi-cal, direct exposure to solar radiation may cause discoloration and surface cracking of the dried product. In indirect-mode drying, these drawbacks are minimized by first heating the air in a solar air heater before directing it over the crop bed [7,8]. In this configuration, the drying chamber is separated from the heating section where the crop is placed [9,10]. Improved temperature control in indirect dryers enhances drying efficiency and results in superior product quality [11]. However, because the air-heating unit and drying chamber are separate, the system becomes more complex and expensive. Despite the higher construction cost, indirect dryers provide better-quality products since the crops are protected from direct solar radiation, thereby reducing discoloration and caramelization effects.

Mixed-mode solar dryers combine the advantages of both direct and indirect systems. In this mode, the crop is directly exposed to solar radiation while preheated air from the solar collector is simultaneously supplied to the drying chamber [12,13]. Consequently, mixed-mode dryers integrate the characteristics of both drying approaches and generally provide improved drying performance [14–15].

Based on the method of air circulation, greenhouse solar dryers can also be classified into natural convection and forced convection systems. Natural convection dryers are referred to as passive solar greenhouse dryers, whereas forced convection dryers are known as active solar greenhouse dryers [16]. In passive systems, airflow is generated naturally because of density differences between hot and cold air. In active systems, fans or blowers are used to transfer heated air from the collector section to the drying chamber. Active greenhouse dryers are generally more efficient and offer better drying control, but they require electrical energy to operate the fans or blowers [17]. This dependency on electricity limits their application in remote regions where power supply is unstable or unavailable. Nevertheless, active systems are more suitable for drying larger quantities of crops and achieving uniform drying conditions. To address the electricity requirement, recent research focuses on integrated solar dryers in which photovoltaic (PV) modules provide the necessary electrical power for operating fans or blowers.

Hybrid greenhouse solar dryers utilize thermal energy from solar radiation together with auxiliary energy sources such as fossil fuels or biomass to dry agricultural products efficiently. Furthermore, greenhouse dryers can be categorized according to roof geometry into parabolic, chapel, single-slope, double-slope, and tunnel-type structures [18,19]. Tunnel dryers, which consist of enclosed ducts open at both inlet and outlet ends, are commonly employed for heating air in drying applications. Mobtaker et al. [18] investigated greenhouse dryers with different orientations, shapes, and dimensions, reporting that a single-span greenhouse dryer oriented in the east–west direction received nearly 8% more annual solar energy compared to other configurations. Similarly, Jagadeesh et al. [20] studied six greenhouse dryer designs—parabola, pyramid, igloo, tropical, quonset, and modified quonset—as illustrated in Fig.1. 4. Their findings indicated that, during summer conditions, the internal temperature of greenhouse dryers followed the order: Quonset, Tropical, Pyramid, Parabola, Modified Quonset, Igloo. The Quonset design produced temperatures approximately 64% higher than ambient conditions, outperforming the other configurations.

Greenhouses are widely used not only for drying agricultural products but also for the cultivation of vegetables and flowers [21,22]. This multifunctional capability allows greenhouse systems to operate throughout the year, thereby improving their economic feasibility and cost-effectiveness [23]. The dual-purpose use of greenhouses increases the return on investment. Greenhouse dryers are also commonly referred to as tent dryers, and the Brace Research Institute introduced one of the earliest basic designs for a passive greenhouse dryer featuring an inclined glass roof.

Figure 1.3: Classification of solar greenhouse dryer based on literature review[1]

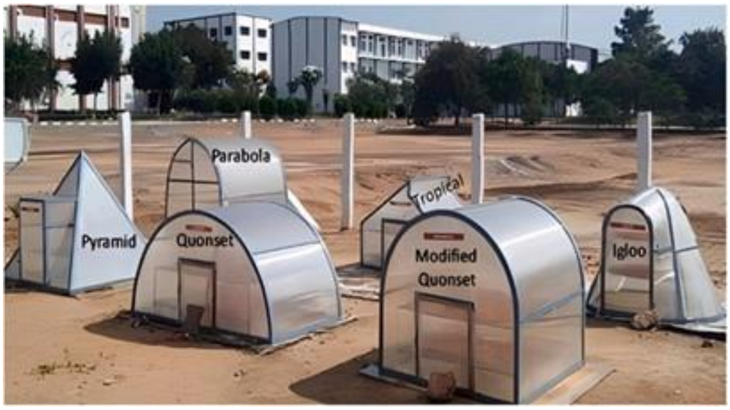

Figure 1.4: Various Greenhouse Dryer Configurations [1].

1.3.2 Classification of solar dryers

There are several methods to categorize solar dryers based on their application or design. Historically, humans have relied on the sun to dry food, either by placing them directly under sunlight or in the shade, a method known as open sun drying. However, in recent years, various solar dryer models have been developed to protect the products from pests, such as insects and rodents. Current solar dryers generally fall into 3 categories, as shown in Fig1. 5: (a) air- circulating dryers; (b) solar-ray dryers; (c) hybrid dryers.

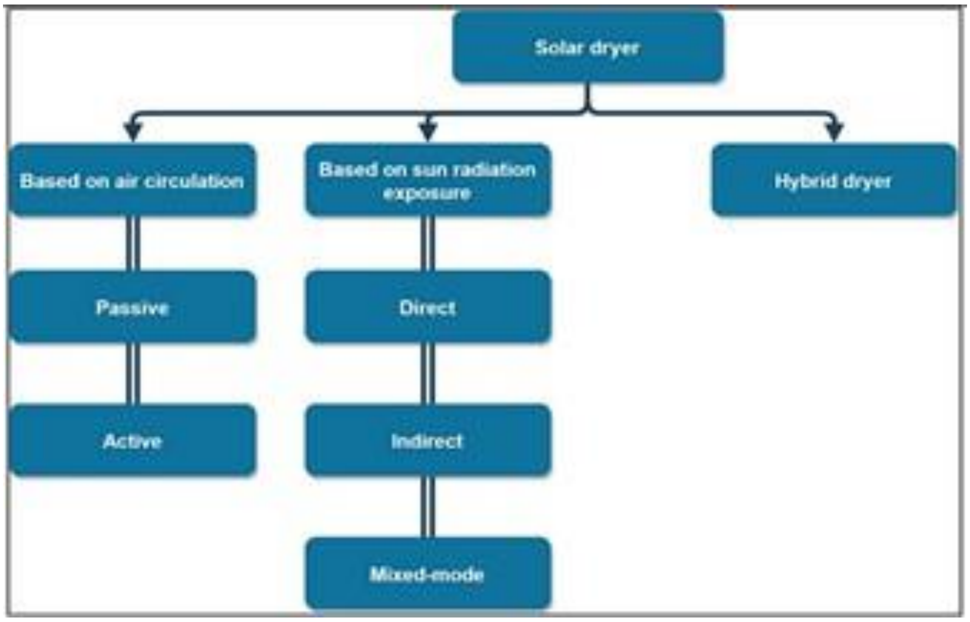

Figure 1.5: Classification of solar dryers[5]

1.3.3 Based on air circulation

These solar dryers are divided into passive and active dryers according on how air is circulated inside of them.

1.3.3.1 Passive solar dryers

Passive solar dryers depend on the natural movement of air, driven by buoyancy, shifts in wind pressure, or a combination of both (Fig.1. 6). Referred to as natural convection solar dryers, they are typically employed for drying small quantities of products at temperatures up to 50°C [24]. These dryers are often used for small-scale applications, such as drying fruits and vegetables at home, and are usually constructed from inexpensive materials. A passive indirect solar dryer was built by Tedesco et al [25] to dry apples, the process took two days in the sun, resulting in an 89% reduction in the initial mass and an approximate 24-month payback period. Also, Gilago et al. [26] dried ivy gourd using an indirect solar dryer, achieving a collector efficiency of 62.56% and more than 6% in drying efficiency, with a payback period of 1.04 years.

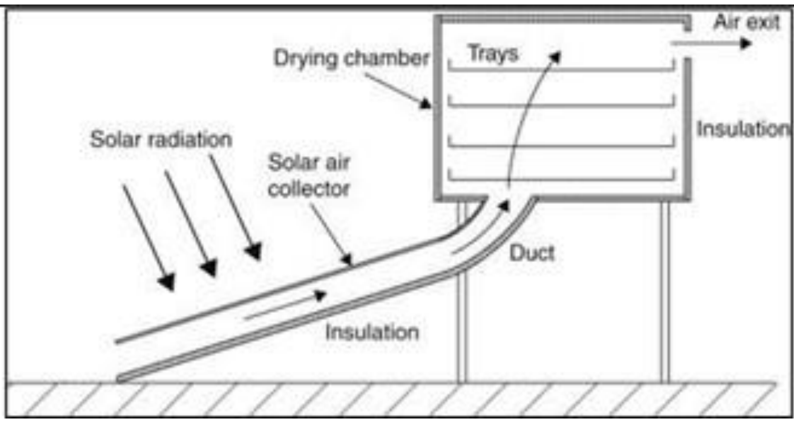

Figure 1.6: Schematic representation of a passive solar dryer [5]

1.3.4 Based on sun radiation exposure

1.3.4.1 Direct solar dryers

These dryers consist of a drying chamber as the entire drying system, with a transparent enclosure made of glass or plastic covering the top, where the item is subjected to direct sunlight, which eliminates moisture from the product (Fig.1.8). Experimentally, Castillo Téllez et al. [27] used forced and natural convection to dehydrate stevia plants within DSD. The results of the experiments demonstrated the technical viability of sun drying and the affordability and ease of use of direct drying. However, this method has limited monitoring over operational conditions, such as temperature, and does not offer insulation from exposure to solar radiation. The effectiveness of a direct solar dryer is primarily influenced by climatic factors, particularly the level of direct solar radiation it receives, leading to a comparatively lower drying rate

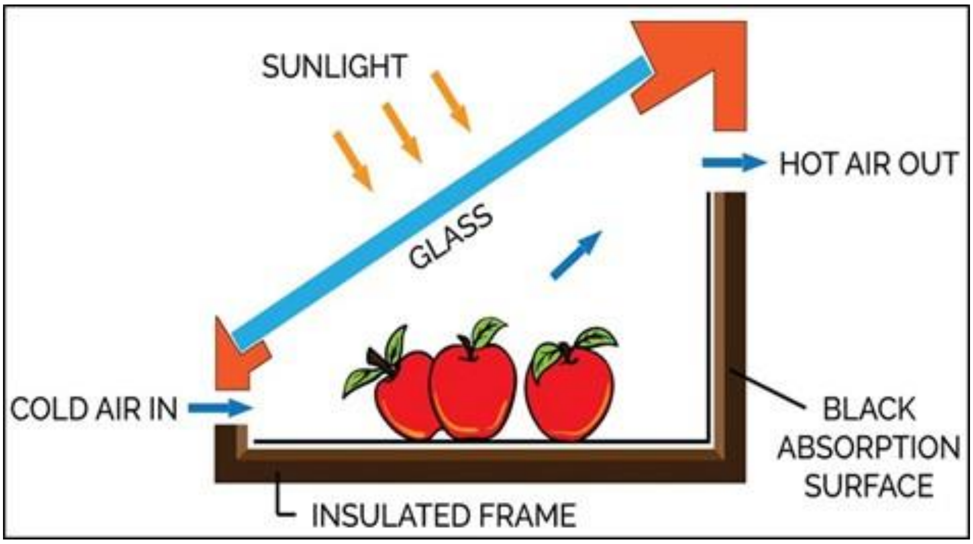

Figure 1.7: Schematic representation of direct solar dryer [5]

1.3.4.2 indirect solar dryers

The items stored in these dryers are shielded from direct solar radiation. One component of the system is a solar collector that transfers heat from the sun to the chamber. Through the output, humid air leaves the chamber after being heated by the SC and removing moisture from the crops (Fig.1.9). Singh et al. [28] developed an innovative indirect solar. After ten days of testing, an average thermal efficiency of 34.1% was achieved. El-Sebaii et al. [29] conducted an experiment drying thyme using an ITSD in forced mode, achieving a cabinet temperature of 54 °C. The process required 5 hours to attain an acceptable level of moisture content. While indirect solar dryers are highly efficient and generate more heat than direct dryers with minimal energy loss through exhaust, they are more expensive than their direct counterparts.

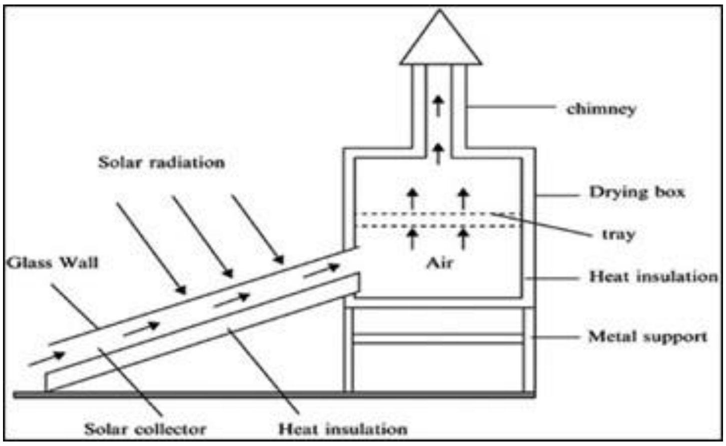

Figure 1.8: Schematic representation of indirect solar dryer [5]

1.3.4.3 Mixed-mode solar dryers

Both direct and indirect solar drying techniques are incorporated into these systems. Similar to an indirect type solar dryer (ITSD), they have a drying chamber and a solar air heater, but because the chamber's ceiling is transparent made of glass or plastic, for example solar radiation can enter both the drying chamber and the solar collector (Fig.1.10). The results of Lakshmi et al. [30] showed that drying stevia leaves required 330 minutes in a mixed-mode solar dryer to attain the required moisture content, and 870 minutes in open sun drying, with a total thermal efficiency of 33.5%. By using more solar energy from the drying cabinet and collector to accelerate the evaporation of water, these dryers can reduce drying periods. Prolonged contact to sunlight, however, could be harmful to certain items.

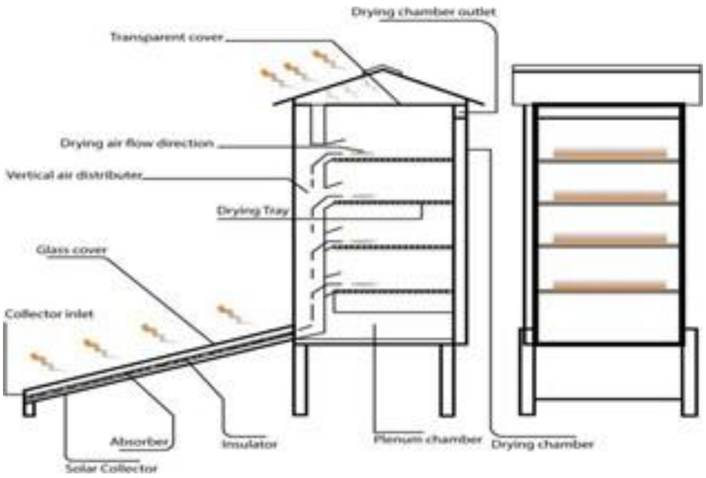

Figure 1.9: Schematic representation of mixed-mode solar dryer [5]

1.3.5 Hybrid dryer

Hybrid dryers refer to systems that utilize both solar radiation and additional energy sources, such as electricity, biomass, or fuel, allowing them to function even when sunlight is insufficient. These external sources, known as auxiliary systems, enable the dryer to operate independently of solar energy (Fig.1.11). While hybrid dryers consume more energy compared to other types, they offer improved efficiency by maintaining operation during low solar radiation. As a result, they are versatile across various climates. However, the need for complex control mechanisms and reliance on alternative energy sources makes these dryers more costly.

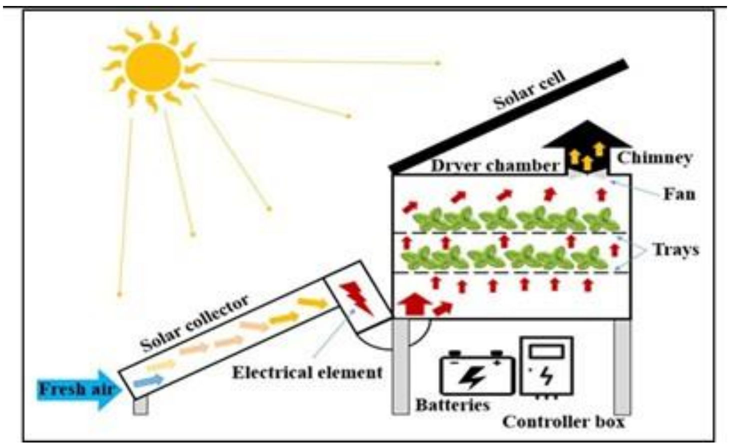

Figure 1.10: hybrid solar dryer [5]

1.4 Conclusion

Based on the comprehensive review and analysis presented in this chapter, it can be concluded that a profound understanding of the radiometric and geometric characteristics of solar energy, alongside a precise grasp of heat and mass transfer mechanisms, constitutes the foundational cornerstone for designing and developing innovative solar drying systems. The extensive literature review highlighted a distinct variation in the efficiency of drying technologies, spanning from traditional Open Sun Drying (OSD) and its associated qualitative degradation and losses to more sophisticated enclosed configurations, such as direct, indirect, and hybrid solar drying systems.

Despite the substantial advantages offered by greenhouse solar dryers, particularly regarding high processing capacities and protection from environmental contaminants, the scientific literature underscores a persistent thermal engineering challenge: the massive thermal losses resulting from the continuous venting of hot, humid air into the ambient environment. This phenomenon significantly impairs overall thermal efficiency, especially under the severe climatic fluctuations characteristic of hyper-arid desert environments like the El-Oued region.

This energetic shortcoming identified in prior studies clearly delineates the research gap that the present study aims to address. It demonstrates that integrating waste heat recovery systems and air recirculation loops represents a promising and sustainable engineering solution to enhance thermal efficiency and stabilize dryer performance.

Building upon the theoretical and methodological foundations established in this chapter, the investigation transitions in Chapter Two (Materials and Methods) to the experimental and practical phase. This next chapter will provide a detailed description of the developed prototype, the experimental procedures, the instrumentation used, and the mathematical modeling deployed to track the drying kinetics and energy performance of the studied product.

Materials and Methods

Chapter 2

Materials and Methods

2.1 Introduction

This chapter is about a study we did at the Research Unit for Renewable Energy Development in Arid Regions at El Oued University. The objective of this study is to describe the experimental setup , we set up our experiment and what methods we used to see how well the new greenhouse dryer works and if it is good for the environment.
The chapter starts by telling you about the dryer and what it is made of. We also explain how it works. Then we talk about how we did the experiments what tools we used to measure things and what rules we followed when we did the drying tests.
We also look really closely at how the system uses energy and we think about how much it costs and how it affects the environment. We want to show that the new greenhouse dryer is an idea and that it can be used in places with lots of sun and not much water, which is where renewable energy is really important. The new greenhouse dryer is what we are focusing on here. We want to see if it can be used in other places with similar conditions like the Research Unit for Renewable Energy Development in Arid Regions, at El Oued University to make the most of renewable energy

2.2 Raw Materials and Sample Preparation

Cucumis melo is one of the most important horticultural crops belonging to the Cucurbitaceae family. It is characterized by a high nutritional value due to its richness in water, natural sugars, and vitamins, particularly vitamins A and C, in addition to essential minerals such as potassium and magnesium. Melon is also an important source of antioxidant compounds, including carotenoids and phenolic compounds, which contribute to its health-promoting properties. Owing to its high moisture content, which generally exceeds 88% on a wet basis, melon is highly perishable after harvest, requiring effective preservation techniques to extend its shelf life [31]. Drying is considered one of the most suitable preservation methods for melon, as it reduces moisture content, limits microbial activity, preserves a significant portion of its nutritional com-ponents, and facilitates storage and transportation while reducing post-harvest losses [32].

The moisture content of Cucumis melo was determined at the Laboratory of the Research Unit for Renewable Energies in Arid Areas (URAER), University of El Oued. Representative melon samples were collected, cut into small pieces, and placed in beakers before being dried in a laboratory oven at 105 °C for 24 h. The moisture content was then calculated using the following relationship:

$$w = \frac{M_i - M_f}{M_i} \times 100 \tag{2.1}$$

Figure 2.1: Fresh Cucumis melo [33]

2.3 Product Preparation

Prior to the drying experiments, the melons were thoroughly washed, peeled, and sliced into uniform slices with a thickness of 0.5 cm to ensure homogeneous drying conditions. The slices were then subjected to a pretreatment by immersion in a 1% citric acid solution for 10 min in order to minimize enzymatic browning and preserve product quality during drying [34,35]. After pretreatment, the slices were drained and uniformly distributed on the drying trays before being loaded into the dryer. Representative samples with the same thickness (0.5 cm) were selected for moisture-loss monitoring throughout the drying process. The sample mass was recorded at variable time intervals, namely every 30 min during the initial stage, every 60 min during the intermediate stage, and subsequently every 120 min and 240 min until moisture equilibrium was reached. In addition, the total mass of the product loaded in the dryer was periodically moni-tored to evaluate the overall drying performance and moisture removal behavior.

Figure 2.2: Cucumis melo Pretreatment

Figure 2.3: Samples of cucumis melo

Figure 2.4: Loading and Distribution of Melon Slices in the Dryer

2.4 Description of the Greenhouse Solar Dryer

The greenhouse dryer used in this study combines the product-quality advantages of indirect solar dryers with the high processing capacity of conventional greenhouse dryers. The system consists of an internal drying chamber measuring 2 m × 1.7 m × 1 m, constructed from 4 cm-thick sandwich panels that provide effective thermal insulation and help maintain stable drying conditions. The external surface of the drying chamber is coated with matte black paint, allowing it to function as a solar absorber by converting incident solar radiation into thermal energy. The dryer is covered by a 0.6 mm transparent polycarbonate sheet positioned 30 cm above the absorber surface, enabling solar radiation transmission while reducing heat losses and protecting the system from environmental conditions. Air circulation is ensured through 200 mm diameter galvanized iron ducts that connect the upper part of the dryer to the drying chamber, while 200 mm diameter ventilation openings located at the lower side of the system facilitate fresh-air intake and improve airflow distribution. The structural rigidity of the dryer is enhanced by metal corner reinforcements installed along its edges. Air extraction and circulation are provided by two 94 W DC fans connected to the drying chamber through 200 mm diameter air ducts, ensuring efficient airflow management and enhanced moisture removal throughout the drying process. In addition, the dryer incorporates an air recirculation system designed to recover part of the exhaust thermal energy. This system redirects the outgoing hot air from the drying chamber toward the external air intake section, where it mixes with ambient air before re-entering the drying chamber. The total length of the recirculation duct is 144 cm [36].

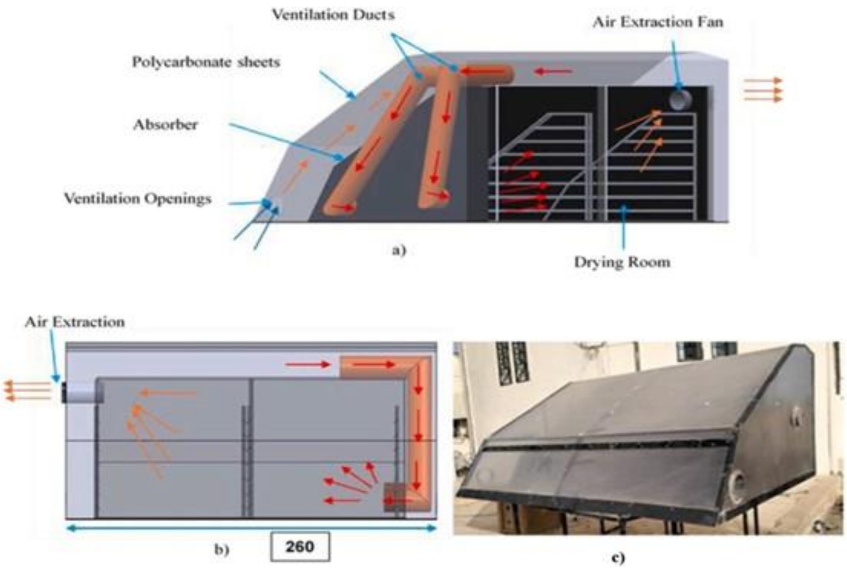

Figure 2.5: Main components of the studied dryer: a three-dimensional schematic diagram and a photographic view [36]

Figure 2.6: Photographs of the developed greenhouse solar dryer used in the present study

Figure 2.7: The exhaust heat recovery system with the developed greenhouse solar dryer

2.5 Working principle of the Greenhouse Solar Dryer

The greenhouse-type dryer uses solar energy and turns it into heat energy to dry agricultural products by using a series of thermal and physical processes.

The dryer has a polycarbonate cover. It lets in wavelength solar radiation as shown in . This radiation hits the metal surface of the drying chamber. The surface is coated with paint to absorb more heat. This process turns radiation into heat energy. This raises the air temperature inside the dryer.

The drying chamber is well-insulated. Its walls are made of sandwich panels. These panels reduce heat loss as shown in (Figure 2.5). This design helps trap heat inside the dryer. It limits the escape of long-wavelength radiation. So the temperature inside the dryer gets much higher than outside.

The heated air is then directed into the drying chamber through metal air ducts as shown in . Air movement happens naturally. This is due to differences in air density. Hot air. Cold air sinks. A fan can also be used to speed up this process. This ensures heat distribution within the drying chamber. This makes the drying process more efficient.

As hot air circulates through the product it transfers heat. This causes the product to warm up and release moisture. Moisture moves from inside the product to its surface. Then it is carried away by the air as water vapor. This process is driven by the difference in vapor pressure between the product and the air.

The air, full of moisture is expelled from the dryer through vents or an extraction fan .

This allows fresh drier air to enter. This keeps the drying process going well.

The dryer also has an internal drying chamber. This protects the product, from solar radiation as shown in (Figure 2.6). This design helps keep the products chemical properties. These include color and shape. The final product quality is better compared to drying methods [37].

2.6 Measurements and instrumentation

During the melon drying experiments, several measuring instruments were employed to continuously monitor the operating conditions and evaluate the thermal performance of the drying system. The measured parameters included temperature, solar radiation, air velocity, relative humidity, and product mass variation throughout the drying process. Accurate measurement of these parameters was essential for analyzing heat and mass transfer phenomena, assessing dryer performance, and determining the drying characteristics of the product under different operating conditions.

2.6.1 Temperature measurement

Temperature measurements were carried out using a BTM-4208SD multi-channel temperature recorder (Lutron Electronic, Taiwan) connected to Type-K thermocouples installed at different locations within the drying system. The device is capable of simultaneously recording temperatures from up to 12 measurement channels, allowing continuous monitoring of the thermal behavior of the dryer. The recorded data were automatically stored on an SD memory card together with the corresponding date and time information, facilitating subsequent data processing and analysis. According to the manufacturer's specifications, the instrument operates within a measurement range of −100 to 1300 °C when used with Type-K thermocouples and provides high measurement accuracy suitable for thermal performance studies.

Figure 2.8: Temperature measurement device

2.6.2 Solar radiation measurement

Solar radiation was measured using a Fluke IRR1-SOL solar irradiance meter, which is specifically designed for solar energy applications. The instrument was employed to continuously monitor the solar radiation incident on the dryer during the experimental period. The device has a measurement range of 0 –1400 W/m² with a resolution of 1 W/m², making it suitable for accurately recording the variations in solar intensity under outdoor conditions. The measured solar irradiance data were used to evaluate the thermal performance of the dryer and to analyze the influence of available solar energy on the drying process. All measurements were expressed in W/m² and were subsequently used in the energy and thermal analyses of the developed drying system.

Figure 2.9: Solar radiation device

2.7 Product Mass Measurement

The mass of the melon samples was measured using a KERN EW precision electronic balance. The balance has a maximum weighing capacity of 220 g and a readability of 0.001 g, ensuring highly accurate measurements of mass variation during the drying process. Throughout the experiments, representative samples were periodically removed from the dryer and weighed at predetermined time intervals to monitor moisture loss and drying progress. The recorded mass data were subsequently used to determine the moisture content, moisture ratio, drying rate, and other drying kinetics parameters. The high precision of the balance contributed to minimizing measurement uncertainty and improving the reliability of the experimental results.

Figure 2.11: Product mass measurement device

2.8 Drying kinetics analyses

The moisture content of the product during drying was evaluated using the moisture ratio (MR), which is one of the most widely used dimensionless parameters for describing and analyzing drying behavior. The moisture ratio provides a convenient representation of moisture removal over time and enables the comparison of drying performance under different operating conditions. It was calculated using the following equation:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (2.2)$$

Where

- MR is the moisture ratio ,
- M_t is the moisture content at time t (kg water/kg dry matter),
- M_0 is the initial moisture content (kg water/kg dry matter),
- M_e is the equilibrium moisture content (kg water/kg dry matter).

2.8.1 Modeling of drying kinetics

The drying behavior of the melon slices was analyzed using a set of widely applied thin-layer drying models presented in Table 3. The experimental data were fitted using **OriginPro** to determine the model that best represents the drying characteristics of the product. The performance of each model was evaluated using the coefficient of determinationR^2, chi-square statistic (χ^2), and root mean square error (RMSE). A model with a higher R^2 value and lower (χ^2) and RMSE values is considered to provide a better representation of the experimental drying data. These statistical parameters were calculated using the following equations:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(MR - MR_{pre,i}\right)^2}{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2} \quad \textbf{(2.3)}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N-z} \quad \textbf{(2.4)}$$

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2} \quad \textbf{(2.5)}$$

- $MR_{\text{exp},i}$: experimental moisture ratio.
- $MR_{\text{pre},i}$: predicted moisture ratio.

Table 2.1: Mathematical models for thin-layer drying [37,38]

No.	Model	Equation
1	Newton	$MR = \exp(-kt)$
2	Page	$MR = \exp(-kt^n)$
3	Modified Page	$MR = \exp(-(kt)^n)$
4	Henderson and Pabis	$MR = a\exp(-kt)$
5	Logarithmic	$MR = a\exp(-kt) + c$
6	Midilli–Kucuk	$MR = a\exp(-kt^n) + bt$
7	Approximation of Diffusion	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$
8	Two term	$MR = a\exp(-k_1 t) + b\exp(-k_2 t)$
9	Two-term exponential	$MR = a\exp(-kt) + (1-a)\exp(-kat)$

- $\overline{MR}_{\exp}$: mean experimental moisture ratio.
- N : number of observations.
- z : number of model constants.

In Eqs. (2-3) to (2-5), $MR_{pre,i}$ and $MR_{exp,i}$ denote the predicted and experimental moisture ratio values, respectively. The parameters (z) and (N) represent the number of model constants and the total number of experimental observations. Furthermore, the moisture diffusion behav-ior of melon slices during the falling rate drying period was analyzed using Fick's second law of diffusion. For modeling purposes, the melon slices were considered as an infinite slab with a constant effective moisture diffusivity, allowing the internal moisture migration process to be adequately described by the diffusion model presented in Eq. (2-6).

$$\frac{\partial MR}{\partial t} = D_{\text{eff}}\nabla^2 MR \quad \textbf{(2.6)}$$

To simplify the diffusion analysis, the melon slices were assumed to behave as infinite slabs with uniform thickness, undergoing drying under homogeneous conditions. It was further assumed that the initial moisture distribution within the product was uniform and that the moisture concentration at the surface instantaneously reached equilibrium with the surrounding drying air. Under these assumptions, moisture migration inside the slices can be adequately described by Fick's diffusion theory, and the geometry of the product may be represented as follows:

The application of Fick's diffusion model was based on the following assumptions:

- The melon slices were considered as infinite and rigid slabs.
- The physical properties of the material remained constant during drying, and shrinkage was neglected.

- Moisture evaporation occurred only at the surface of the slices.
- Mass transfer was assumed to be symmetrical and uniformly distributed throughout the drying process.
- At the beginning of drying, the surface moisture content was assumed to instantaneously reach its equilibrium value.
- The temperature distribution within the product was assumed to be uniform and equal to the drying air temperature.
- The effective moisture diffusivity (D_{eff}) was assumed to remain constant throughout the drying process.

by applying the above assumption, is it possible to determine analytical solution of diffusion equation, which founded by Crank (Eq. (9)) [38]:

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{(2n+1)^2\pi^2 D_{eff}t}{4L^2}\right) \qquad \textbf{(2.7)}$$

- MR is the moisture ratio (-).
- D_{eff} is the effective moisture diffusivity (m^2/s).
- t is the drying time (s).
- L is the half-thickness of the slice (m).
- n is a positive integer.

in Eq. (2-6), D_{eff} is the effective moisture diffusivity, t is the drying time, L denotes the half thickness of the slice, and n is a positive integer. As drying progresses, the contribution of the higher-order terms in the series decreases significantly. Consequently, for long drying times, Eq. (2-6) can be approximated by its first term only, resulting in the simplified form given in Eq. (2-7).

$$MR = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}t}{4L^2}\right) \qquad \textbf{(2.8)}$$

And

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \frac{\pi^2 D_{eff}t}{4L^2} \qquad \textbf{(2.9)}$$

To determine the effective diffusivity, the following calculation is used Eqs.(2-8), (2-9):

$$MR = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff} t}{4L^2}\right) \quad \textbf{(2.10)}$$

$$D_{eff} = -\frac{Slope(k) \cdot 4L^2}{\pi^2} \quad \textbf{(2.11)}$$

2.9 Conclusion

This chapter presented the experimental methodology adopted to evaluate the performance of the developed greenhouse solar dryer integrated with an exhaust heat recovery system. The drying product, dryer configuration, and measuring instruments were described, followed by the mathematical models used for drying kinetics analysis and the procedure for determining effective moisture diffusivity. These methodologies provide the basis for analyzing the thermal behavior, drying characteristics, and moisture transfer mechanisms of the investigated system. The experimental results and their discussion are presented in the following chapter.

Having established the experimental methodology, system components, and the mathematical frameworks for drying kinetics in this chapter, it is essential to evaluate how the developed system performs under real meteorological conditions. The next chapter (Chapter 3) will present and discuss the experimental results, focusing on the thermal behavior of the greenhouse solar dryer, the impact of the heat recovery system, and the statistical validation of the thin-layer drying models for cantaloupe slices.

Results and Discussion

Chapter 3

Results and Discussion

3.1 Introduction

This chapter outlines the experimental methodology, material preparation, and theoretical framework adopted to evaluate the performance of the newly developed greenhouse solar dryer integrated with an exhaust heat recovery system. All experimental trials were conducted under the arid climatic conditions of El Oued Province, specifically at the Research and Development Unit for Renewable Energies in Arid Zones (URERMS), associated with the University of Echahid Hamma Lakhdar.

The chapter is systematically structured into several key sections to provide a comprehensive understanding of the research methodology. First, it describes the raw material used in this study, which is Cantaloupe (Cucumis melo), along with the specific physical and chemical pretreatments applied to ensure homogeneous drying conditions and maintain product quality. Second, a detailed engineering description of the developed greenhouse solar dryer, its dimensions, structural materials, and the mechanism of the integrated air recirculation and heat recovery system is presented. Third, the instrumentation and measurement devices utilized for continuous monitoring of key operating parameters including temperature, solar irradiance, airflow velocity, and product mass loss are detailed along with their technical specifications. Finally, this chapter establishes the mathematical and theoretical modeling framework used to analyze the drying kinetics. This includes the equations for determining the moisture ratio (MR), the selection of standard thin-layer empirical models, and the analytical solution of Fick's second law of diffusion used to calculate the effective moisture diffusivity (D_{eff}) of the product. Through this rigorously structured approach, a reliable basis is established for interpreting the thermal and physical phenomena discussed in the subsequent results section.

3.2 Thermal performance

To evaluate the performance of the newly developed dryer, temperature measurements were conducted at different locations within the drying system as well as in the ambient environment. The temperatures were recorded at the absorber plate, the inlet of the drying chamber, the middle of the drying chamber, and the outlet of the drying chamber. Temperature data were collected at 10-minute intervals throughout the drying process. The recorded temperature profiles are presented in the following figures.

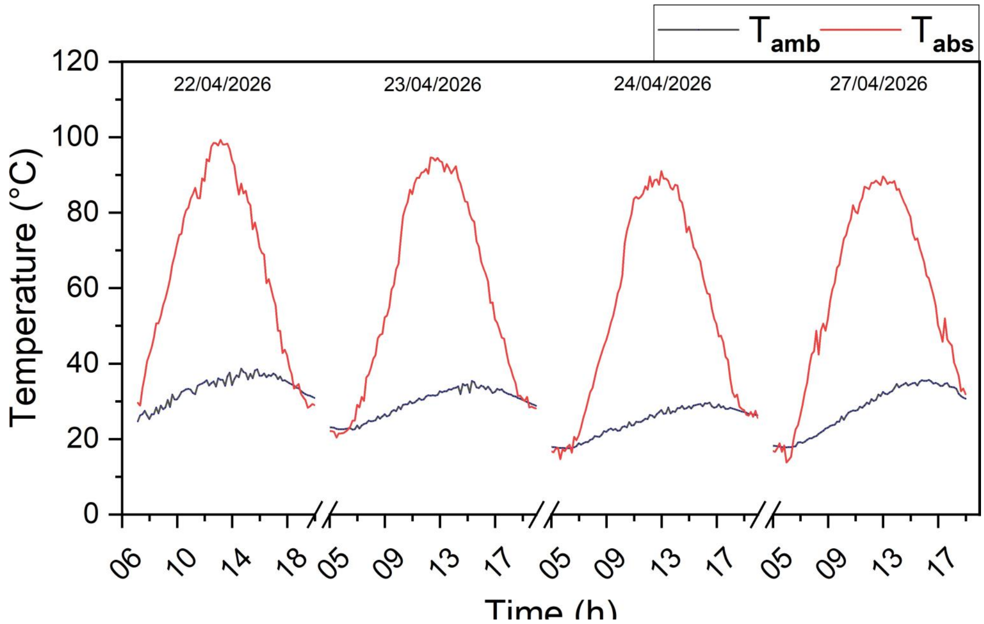

Figure 3.1: Temperature of absorber

The figure Figure 3.1 illustrates the evolution of the absorber element temperature (T_{abs}) compared to the ambient temperature (T_{amb}) over the four drying days. It is observed that both curves follow the daily pattern of solar radiation, where temperatures rise gradually after sunrise, reach their peak values during the midday period, and then decrease progressively with the decline in radiation intensity until the end of the day.However, the absorber tempera-ture recorded significantly higher values than the ambient temperature throughout the operating period; the peak values for the absorber ranged between 88°C and 99°C, while the ambient tem-perature did not exceed approximately 38°C. This substantial thermal gradient reflects the high capability of the absorber element to absorb solar radiation and convert it into thermal energy, which contributes to heating the air directed into the drying chamber.Additionally, the rapid rise in the absorber element temperature during the morning hours indicates a good thermal responsiveness of the system, whereas the gradual decline after midday is associated with the decrease in solar radiation incident on the absorber surface. Despite the daily fluctuations in weather conditions, the absorber maintained consistently high and comparable temperatures across the different days of the experiment, indicating the stability of the dryer's thermal performance and its efficiency in providing the necessary thermal energy for the drying process.The large thermal gap between Tabs and Tamb, which exceeded 60°C during certain periods, confirms the effective-ness of the absorber design in capturing solar energy and minimizing heat losses. From a thermodynamic perspective, the substantial thermal gradient between Tabs and Tamb, which reached up to 61°C, is attributed to two primary factors: the optical properties of the absorber and the greenhouse effect trapped within the collector structure.

The application of matte black paint significantly enhances the solar absorptivity coefficient of the absorber plate while maintaining low emissivity. Simultaneously, the transparent polycarbonate cover sheet plays a crucial role by allowing short-wave solar radiation to pass through while blocking the long-wave infrared radiation emitted by the heated absorber plate. This mechanisms creates a highly efficient greenhouse effect and isolates the absorber from external convective cooling caused by ambient wind, thereby ensuring a high rate of thermal energy conversion This reflects positively on raising the drying air temperature and improving the moisture removal rate from the dried product.

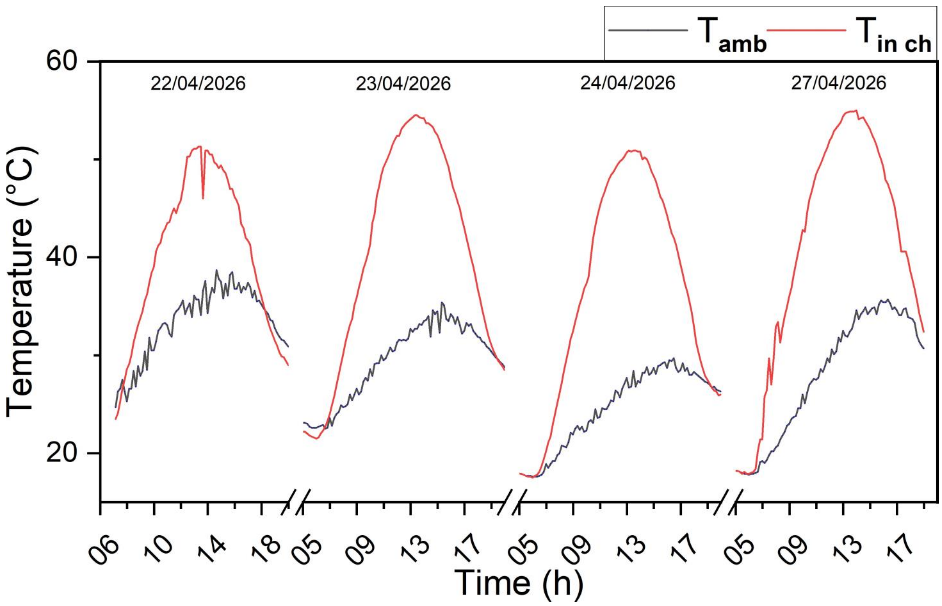

Figure 3.2: Temperature at the inlet of the drying chamber

y

The figure Figure 3.2 illustrates the evolution of the drying chamber inlet air tempera-ture ($T_{in\ ch}$) compared to the ambient temperature (T_{amb}) during the days of the experiment. It is observed that the air temperature at the chamber inlet rises significantly above the ambient temperature throughout the daytime operating period; the peak values reached between 50°C and 55°C, while the ambient temperature ranged approximately between 30°C and 38°C. This thermal gradient confirms the dryer's capability to elevate the air temperature before it enters the drying chamber, thereby providing the appropriate thermal conditions to increase the moisture evaporation rate from the product.Additionally, the $T_{in\ ch}$ curve follows the same trend recorded for the absorber element temperature (T_{abs}); the values rise gradually from the morning, peak during the midday hours, and then decrease with the decline in solar radiation intensity. This be-havior reflects the direct relationship between the two variables, as the thermal energy absorbed by the absorber element is transferred to the air flowing over it via convection. Consequently, the air gains a portion of this energy before entering the drying chamber. Therefore, the substantial rise in the absorber element temperature reaching limits of 88–99°C led to an increase in the inlet air temperature by about 15–25°C above the ambient temperature.It is also noted that the chamber inlet temperature remains lower than the absorber element temperature across all operating periods. This is a natural consequence resulting from the transfer of only a portion of the heat to the air, alongside the presence of thermal losses associated with convection, radiation, and conduction. Nevertheless, the clear alignment between the T_{abs} and $T_{in\ ch}$ curves demon-strates the efficiency of the heat exchange process between the absorber element and the air. It further confirms that the high thermal performance of the absorber element directly translated into heating the drying air and improving the drying conditions inside the chamber The fact that the inlet air temperature (Tin,ch) remained consistently lower than the absorber temperature (Tabs) is a typical behavior in indirect solar thermal collectors. This temperature drop represents the convective heat transfer resistance between the solid absorber plate and the flowing air stream, as well as minor thermal losses through the insulated galvanized ducts. However, maintaining Tin,ch within the range of 50°C to 55°C during peak hours is highly favorable for food drying. This temperature level significantly lowers the relative humidity of the drying air, thereby increasing its moisture absorption capacity without exposing the sensitive agricultural product (cantaloupe slices) to thermal degradation or case hardening.

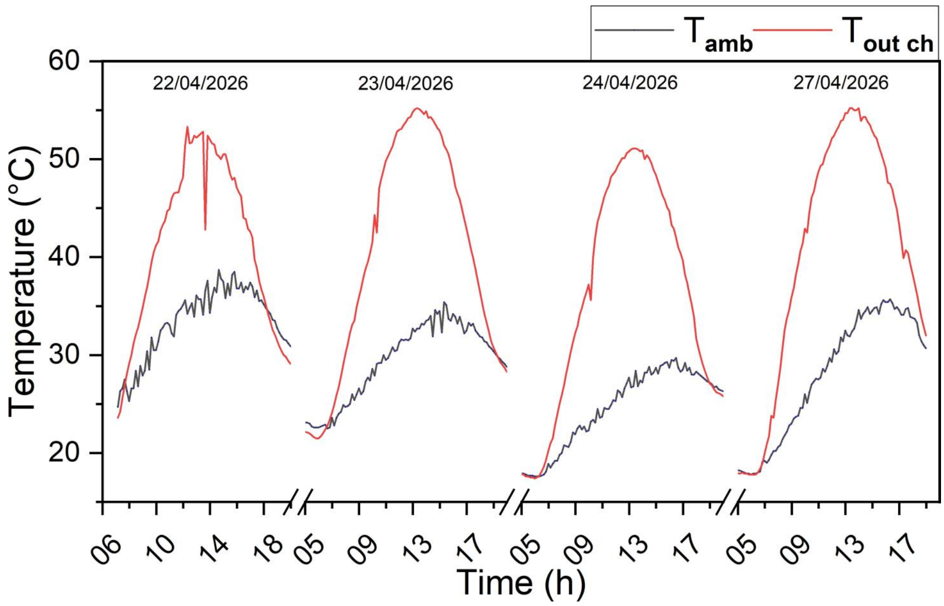

Figure 3.3: Temperature at the outlet of the drying chamber

The figure Figure 3.3 illustrates the evolution of the drying chamber outlet air temperature ($T_{out,ch}$) compared to the ambient temperature (T_{amb}) during the days of the experiment. It is observed that the air temperature at the chamber outlet follows the same daily pattern recorded for the absorber element temperature (T_{abs}), rising gradually from the morning hours to reach its peak values during the midday period, and then decreasing with the decline in solar radiation in-tensity. The maximum values of the outlet temperature ranged approximately between 51°C and 55°C, which is significantly higher than the ambient temperature that did not exceed 35–38°C on most days. This indicates the effectiveness of the system in providing an appropriate ther-mal medium to sustain the drying process.This behavior is directly linked to the performance of the absorber element, as the increase in its temperature up to 88–99°C leads to heating the air passing through the solar collector before it enters the drying chamber. After the air traverses the inside of the chamber and undergoes heat and mass transfer with the cantaloupe slices, it exits at a relatively high temperature despite losing a portion of its thermal energy in evapo-rating moisture. Consequently, the outlet temperature remained substantially higher than the

ambient temperature throughout the entire operating period.It is also noted that the Tout,ch curve is very close to the chamber inlet air temperature curve, with slightly lower values recorded during certain periods due to the consumption of a portion of the thermal energy in the process of water evaporation from the product. This indicates that the thermal energy provided by the absorber element was sufficient to maintain high temperatures inside the drying chamber along the entire airflow path, which confirms the efficiency of the absorber in supplying the system with the necessary thermal energy and demonstrates the stability of the dryer's thermal perfor-mance across the different days of the experiment.The clear alignment between the evolution of Tabs and Tout,ch confirms that the absorber element represents the primary source of thermal energy within the system. Any increase in its temperature directly translates into a rise in the temperature of the air leaving the drying chamber, which contributes to enhancing heat and mass transfer rates and improving overall drying efficiency Crucially, the close proximity between the inlet temperature (Tin,ch) and the outlet temperature (Tout,ch) provides strong evidence of the efficiency of the integrated exhaust heat recovery system. In conventional indirect solar dryers without recirculation, the exhaust air is discharged into the environment, leading to massive sensible heat losses. In this developed system, the heat recovery duct successfully intercepts this hot exhaust air (which carries valuable thermal energy at 51–55°C) and blends it back with the incoming fresh ambient air. This continuous thermal feedback loop significantly reduces the heating load required from the solar absorber, stabilizes the internal microclimate of the drying chamber against solar radiation fluctuations, and minimizes total thermal energy rejection to the ambient environment.

3.2.1 Performance of the Novel Greenhouse Dryer (NGHD) for melon Drying

The curve Figure 3.4 represents the evolution of the moisture content of melon slices on a dry basis during the drying process, where it decreases gradually from a high initial value of approximately 9.4 kg water/kg dry matter to a very low final value approaching zero after about 2000 minutes. It is observed that the decrease is sharp during the initial stages of drying due to the abundance of free moisture present on the surface of the slices and in the layers close to it, which facilitates water transfer to the surrounding environment and leads to a high drying rate.As the process continues, the moisture content decreases at a slower rate due to the depletion of the bulk of the surface moisture, causing water movement within the material to be governed mainly by the internal diffusion mechanism from the plant tissues toward the surface. This deceleration becomes clearly pronounced after about 700 minutes, where only the bound moisture within the cellular structure of the cantaloupe remains, which requires longer time and higher energy to remove. After around 1200 minutes, the curve approaches a state of stability, indicating that the product is nearing moisture equilibrium with the drying air, such that changes in moisture content become very negligible.This behavior confirms that the drying process of cantaloupe slices takes place mainly during the falling rate period, which is the characteristic stage for most agricultural products, where internal moisture diffusion dominates the drying mechanism. Furthermore, the significant reduction in moisture content from about 9.4 to less than 0.1 kg water/kg dry matter reflects the high efficiency of the drying system in removing moisture, enhancing product stability, and extending its shelf life.

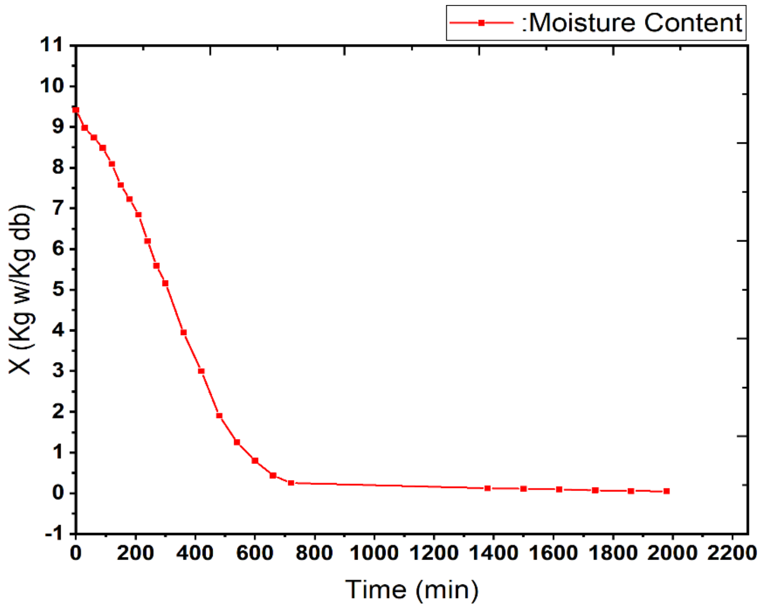

Figure 3.4: Moisture contente of melon

3.3 Empirical models of thin layer drying process

In this section, the results of the mathematical modeling of the drying kinetics of melon slices are presented. Among the tested models, the Modified Page model was found to be the most suitable for predicting the drying behavior of the studied system, as it exhibited the highest coefficient of determination (R^2) and the lowest chi-square value (χ^2) compared with the other evaluated models.

Table 3.1: Drying kinetic models parameters for NGHD

Model	K_1	K_2	n	a	b	R^2	χ^2
Newton	0.00248	–	–	–	–	0.94197	0.00849
Page	2.24289×10^{-5}	–	1.8037	–	–	0.99731	3.94177×10^{-4}
Modified Page	0.00288	–	–	1.13048	–	0.97531	0.00326
Henderson and Pabis	-3.37×10^{-9}	144316	–	-144316	–	0.95895	0.00591
Logarithmic	-3.37×10^{-9}	144316	–	-144316	–	0.68007	0.04195
Midilli–Kucuk	8.67×10^{-6}	–	1.9558	0.96481	4.77×10^{-7}	0.99878	2.05×10^{-4}
Approximation of Diffusion	0.00249	–	1.02096	1.19124	358.71432	0.96262	0.00525

3.4 Conclusion

In conclusion, this chapter successfully evaluated the experimental data and performance of the developed greenhouse solar dryer. The results verified that the heat recovery system effectively decreased thermal losses by recirculating hot exhaust air. Furthermore, the thin-layer drying behavior of cantaloupe was comprehensively analyzed, proving that the system provides a stable and optimized microclimate for agricultural preservation in arid environments.

General Conclusion

This study represents an applied scientific contribution to the field of enhancing the thermal performance of greenhouse solar drying systems in arid and desert environments. Experimental outcomes and thermodynamic analyses demonstrated that integrating a heat recovery system and a solar collector achieved a substantial enhancement in the system's thermal efficiency. This was accomplished by raising the drying air temperature, ensuring its homogeneous flow, and reducing the relative humidity within the drying chamber. This stable thermal behavior accelerated the moisture removal rate and significantly reduced drying time, while protecting the sensitive bioactive compounds of the product from photodegradation and thermal degradation.

Furthermore, the experimental results confirmed the efficacy of the developed system in utilizing available solar energy with higher efficiency compared to conventional systems. The heat recovery system contributed to reusing a significant portion of the lost thermal energy, which reflected positively on the stability of the operating conditions inside the dryer and improved its energy yield. The drying kinetics study showed good agreement between the experimental data and the adopted mathematical models, which enhances the reliability of predicting drying behavior and the possibility of employing these models to design more efficient systems in the future.

From a practical standpoint, the importance of this work lies in providing a technological solution tailored to the prevailing climatic conditions in desert regions, particularly in the El Oued region. It achieves this by delivering a sustainable, low-energy-consumption drying system capable of reducing agricultural waste and improving the quality of dried products. Moreover, this study opens promising research horizons for developing more advanced hybrid solar dryers by integrating thermal storage technologies, smart control systems, or auxiliary energy sources, thereby contributing to enhancing food security, optimizing energy consumption, and supporting sustainable agricultural development in regions with high solar potential.

References

[1] Kumar, A., & Kumar, A. (2026). Comprehensive review of integrated greenhouse drying systems for sustainable development and performance analysis. Renewable and Sustainable Energy Reviews, 226, 116232. https://doi.org/10.1016/j.rser.2026.116232

[2] Jain D, Tiwari GN. Thermal aspects of open sun drying of various crops. Energy 2003;28. https://doi.org/10.1016/S0360-5442(02)00084-1.

[3] Mulet A, Berna A, Rossello ´ C, Canellas ˜ J. Analysis of open sun drying experiments. Dry Technol 1993;11. https://doi.org/10.1080/07373939308916905.

[4] Abdalla M, Babiker AMOA, Khiar UEHM, Elhesain MHA, Idriss SHE, Figeada SOA. Comparative study between open-direct Sun and solar drying of onion slices (Allium cepa L.). Opsearch: Am J Open Res 2023;2. https://doi.org/10.58811/ opsearch.v2i6.16.

[5] Kherrafi, M.A., et al., Advancements in solar drying technologies: Design variations, hybrid systems, storage materials and numerical analysis: A review. Solar Energy, 2024. 270: p. 112383.

[6] Babi´c M, Babi´c L. Advantages and disadvantages of direct and indirect drying of mercantile grain and seeds. J Pocess Energy Agric 2020;24. https://doi.org/ 10.5937/jpea24-29698.

[7] Saikia D, Kumar Nayak P, Radha Krishnan K, Kondareddy R, Lakshmi DVN. Development of indirect type solar dryer and experiments for estimation of drying parameters of dhekia (Diplazium esculentum). Mater Today Proc 2022;56. https://doi.org/10.1016/j.matpr.2022.02.255.

[8] Essalhi H, Benchrifa M, Tadili R, Bargach MN. Experimental and theoretical analysis of drying grapes under an indirect solar dryer and in open sun. Innov Food Sci Emerg Technol 2018;49. https://doi.org/10.1016/j.ifset.2018.08.002.

[9] Hatami S, Payganeh G, Mehrpanahi A. Energy and exergy analysis of an indirect solar dryer based on a dynamic model. J Clean Prod 2020;244. https://doi.org/ 10.1016/j.jclepro.2019.118809.

[10] Sami S, Etesami N, Rahimi A. Energy and exergy analysis of an indirect solar cabinet dryer based on mathematical modeling results. Energy 2011;36. https:// doi.org/10.1016/j.energy.2011.02.027.

[11] Kokate YD, Baviskar PR, Baviskar KP, Deshmukh PS, Chaudhari YR, Amrutkar KP. Design, fabrication and performance analysis of indirect solar dryer. Mater Today Proc 2023;77. https://doi.org/10.1016/j.matpr.2022.11.439.

[12] Afzal A, Iqbal T, Ikram K, Anjum MN, Umair M, Azam M, et al. Development of a hybrid mixed-mode solar dryer for product drying. Heliyon 2023;9. https://doi. org/10.1016/j.heliyon.2023.e14144.

[13] Gyawali M, Acharya A, Adhikari T, Dahal K, Kafle B, Kim DH, et al. A mixedmode ginger and turmeric solar dryer: design, simulation, biochemical and performance analysis. Bibechana 2022;19. https://doi.org/10.3126/bibechana. v19i1-2.46386.

[14] Ekka JP, Palanisamy M. Performance assessments and techno and enviroeconomic analyses on forced convection mixed mode solar dryer. J Food Process Eng 2021;44. https://doi.org/10.1111/jfpe.13675.

[15] Tefera E, Gardie Damtie E, Bezzie YM, Admass Z. Experimental testing of mixedmode double pass solar air heater integrated with aluminium cans for red pepper drying. Case Stud Therm Eng 2023;50. https://doi.org/10.1016/j. csite.2023.103379.

[16] Kumar S, Dewangan N, Verma G, Ghritlahre HK, Verma M, Kumar Y, et al. Performance analysis of natural and forced convection mixed mode UV tent house solar dryer for potato drying. Energy Sources, Part A Recovery, Util Environ Eff 2023;45. https://doi.org/10.1080/15567036.2023.2259839.

[17] Kumar M, Shimpy Sahdev RK, Sansaniwal SK, Bhutani V, Manchanda H. Experimental forced convection greenhouse and indirect cabinet drying of date fruits: a comparative study. J Therm Anal Calorim 2023;148. https://doi.org/ 10.1007/s10973-023-12057-9.

[18] Zziwa A, Okello AW, Kabenge I, Matsapwe D, Kizito SS, Paul S, et al. Optimizing solar drying: a critical review of shapes, orientation, and future prospects for hybrid solar dryers. J Power Energy Eng 2023;11. https://doi.org/10.4236/ jpee.2023.1112004.

[19] Vivekanandan M, Periasamy K, Babu CD, Selvakumar G, Arivazhagan R. Experimental and CFD investigation of six shapes of solar greenhouse dryer in no load conditions to identify the ideal shape of dryer. Mater Today Proc 2020;37. https://doi.org/10.1016/j.matpr.2020.07.062.

[20] Jagadeesh D, Vivekanandan M, Natarajan A, Chandrasekar S. Experimental conditions to identify the ideal shape of dryer investigation of six shapes of solar greenhouse dryer in no load. Mater Today Proc 2020;37. https://doi.org/ 10.1016/j.matpr.2020.05.386.

[21] Mellalou A, Riad W, Mouaky A, Bacaoui A, Outzourhit A. Optimum design and orientation of a greenhouse for seasonal winter drying in Morocco under constant volume constraint. Sol Energy 2021;230. https://doi.org/10.1016/j. solener.2021.10.050.

[22] Colorado A, Morales O, Ossa D, Amell A, Chica E. Modeling the optimal condition for drying rumen contents using a solar greenhouse dryer. Case Stud Therm Eng 2022;30. https://doi.org/10.1016/j.csite.2021.101678.

[23] Aghbashlo M, Müller J, Mobli H, Madadlou A, Rafiee S. Modeling and simulation of deep-bed solar greenhouse drying of chamomile flowers. Dry Technol 2015;33. https://doi.org/10.1080/07373937.2014.981278.

[24] Kamarulzaman, A., M. Hasanuzzaman, and N.A. Rahim, Global advancement of solar drying technologies and its future prospects: A review. Solar Energy, 2021. 221: p. 559- 582.

[25] Tedesco, F.C., A.J. Bühler, and S. Wortmann, Design, Construction, and Analysis of a Passive Indirect Solar Dryer With Chimney. Journal of Solar Energy Engineering, 2018. 141(3).

[26] Gilago, M.C., V. Reddy Mugi, and C. V.P, Energy-exergy and environ-economic (4E) analysis while drying ivy gourd in a passive indirect solar dryer without and with energy storage system and results comparison. Solar Energy, 2022. 240: p. 69-83

[27] Castillo Téllez, M., et al., Solar drying of Stevia (Rebaudiana Bertoni) leaves using direct and indirect technologies. Solar Energy, 2018. 159: p. 898-907.

[28] Singh, S., et al., A novel active-mode indirect solar dryer for agricultural products: Experimental evaluation and economic feasibility. Energy, 2021. 222: p. 119956.

[29] El-Sebaii, A.A. and S.M. Shalaby, Experimental investigation of an indirect-mode forced convection solar dryer for drying thymus and mint. Energy Conversion and Management, 2013. 74: p. 109-116.

[30] Lakshmi, D.V.N., et al., *Performance analyses of mixed mode forced convection solar dryer for drying of stevia leaves.* Solar Energy, 2019. **188**: p. 507-518.

[31] McDermott, A. (2025, April 22). *6 Nutritious benefits of eating cantaloupe* (J. Jones, Med. Rev.). Healthline. https://www.healthline.com/health/food-nutrition/benefits-of-cantaloupe

[32] Bennamoun, L. and A. Belhamri, Using solar thermal energy for drying of fresh food products in Algeria. 2010.

[33] https://profert.dz/ar/?p=14227

[34] DiPersio, P. A., Kendall, P. A., & Sofos, J. N. (2006). Sensory evaluation of home dried fruit prepared using treatments that enhance destruction of pathogenic bacteria. *Journal of Food Quality*, 29(1), 47-64. https://www.researchgate.net/publication/229725997

[35] Zepp, M. (2018, July 10). Preserving color and preventing browning of foods. Penn State Extension. https://ucanr.edu/sites/default/files/2020-10/337761.pdf.

[36] Zine, A., Benseddik, A., Saim, R., Zelaci, M., Laouini, A., Mansouri, K., Kherrafi, M. A., Khaled, M. T. O., & Guediri, S. (2025). Performance and sustainability assessment of a greenhouse dryer with integrated sunlight protection for mint drying. Renewable Energy, 244, Article 122723.

[37] Sileshi, S.T., A.A. Hassen, and K.D. Adem, Simulation of mixed-mode solar dryer with vertical air distribution channel. Heliyon, 2022. 8(11).

[38] Parhizi, Z., et al. Modeling and Optimization of Energy and Exergy Parameters of a Hybrid-Solar Dryer for Basil Leaf Drying Using RSM. Sustainability, 2022. 14, DOI: 10.3390/su14148839.