الجمهورية الجزائرية الديمقراطية الشعبية

République Algérienne Démocratique et Populaire

وزارة التعليم العالي والبحث العلمي

Ministère de l'enseignement supérieur et de la recherche scientifique

Université Mohamed Khider – Biskra

جامعة محمد خيضر بسكرة

Faculté de la technologie

كلية التكنولوجيا

Département : Génie mécanique

قسـم: الهندسة الميكانيكية

Réf :………………

المرجع :............

جامعة محمد خيضر بسكرة

Thèse présentée en vue de l'obtention

Du diplôme de

Doctorat en sciences

Spécialité : Energétique

Conception et réalisation d'un séchoir cylindro-parabolique pour les produits agro-alimentaire de la région d'eloued

Présentée par :

LAOUINI Abdeldjalil

Soutenue publiquement le 27/02/2023

Devant le jury composé de :

Devant le jury composé de :

GUERIRA Belhi	**MCA**	**Président**	**Université de Biskra**
MENECEUR Redha	**MCA**	**Examinateur**	**Université d'El oued**
MERZOUGUI Abdelkrim	**MCA**	**Examinateur**	**Université de Biskra**
BENHAOUA Boubaker	**Pr**	**Rapporteur**	**Université d'El oued**
AOUES Kamel	**MCA**	**Co- Rapporteur**	**Université de Biskra**

Année Universitaire 2022/2023

بسم الله الرحمن الرحيم

يرفع الله الذين آمنوا منكم والذين أوتوا العلم درجات

صدق الله العظيم

Dedication

To my parents

To my Brothers

To all my teachers

To my family

To my friends

Thanks

I want to express my sincere gratitude to my advisor **Prof. B. BENHAOUA** (University Of Eloued), for his excellent guidance, valuable advice, strong support, and continuous encouragement throughout the course of this research work at Biskra University. It has been a great pleasure and privilege to work under his supervision toward completion of this research.

I also thank **Prof. K. AOUES** (University of Biskra), for having co-supervised this thesis work.

I sincerely thank **Prof. B. GUERRIRA** (University of Biskra), for his continuous encouragement, guidance and support throughout my study, also for being the president of the supervisory committee members of my thesis.

I greatly acknowledge the supervising committee members, **Prof. A.K. MERZOUGUI** and **Dr. R. MENECEUR** from UHL-ELOUED; I would also like to appreciate all their guidance, suggestions and comments for improving this thesis.

I wish to express my deepest gratitude to all my colleagues of Mechanical Engineering Department at UHL-ELOUED for their helpful technical discussions and suggestions during the preparation of my thesis.

Abstract/Resumé/ملخص

Résumé :

Dans le domaine de la technologie de séchage, les méthodes de séchage traditionnelles sont considérées comme moins efficaces et chronophages. La présente étude vise à développer le séchoir solaire indirect pour les produits agro-alimentaires de la région d'El-Oued (Sud-Est de l'Algérie) notamment l'arachide. Le séchoir utilise un concentrateur parabolique pour améliorer ses performances en augmentant sa température et par conséquent une diminution du temps de séchage. Le séchoir solaire réalisé, dans ce travail, a été testé sur les piments rouges durant avril 2018 et 2020. La température dans la chambre de séchage est atteinte enivrante 55 °C avec un temps de séchage de 5 h, alors que le taux de séchage soit le teneur en eau passe 47 to 9% pour l'arachide et pour piment rouge le taux d'humidité dimunue de 90% à l'équilibre durant 5 heures.

Mots clés : Séchage Solaire ; Concentrateur Parabolique ; Cinétique de Séchage ; Base Humide ; Système de Poursuit.

Abstract:

In the field of drying technology, traditional drying methods are considered less efficient and time-consuming. The present study aims to develop an indirect solar dryer for agricultural products in the El-Oued region (Southeast Algeria), particularly peanuts. The dryer utilizes a parabolic concentrator to enhance its performance by increasing the temperature and thus reducing the drying time. The solar dryer developed in this work was tested on red chilli during April 2018 and 2020. The temperature in the drying chamber reached an impressive 55°C with a drying time of 5 hours, while the drying rate, i.e., the moisture content, decreased from 47% to 9% for peanuts, and for red chilli, the moisture content decreased from 90% to equilibrium within 5 hours.

Keywords: Solar drying; Dish concentrator; drying kinetics; wet basis; Tracking system.

ملخص:

في مجال تقنية التجفيف، تُعتبر طرق التجفيف التقليدية غير فعالة وتستغرق وقتًا طويلاً. تهدف هذه الدراسة إلى تطوير مجفف شمسي غير مباشر للمنتجات الزراعية في منطقة الوادي (جنوب شرق الجزائر)، ولا سيما الفول السوداني.

يستخدم المجفف تجميعًا قطعيًا محوريًا لتعزيز أدائه من خلال زيادة درجة الحرارة وبالتالي تقليل وقت التجفيف. تم اختبار المجفف الشمسي الذي تم تطويره في هذا العمل على الفلفل الأحمر خلال أبريل 2018 و 2020. بلغت درجة الحرارة في غرفة التجفيف 55 درجة مئوية بزمن تجفيف يبلغ 5 ساعات، في حين انخفضت نسبة التجفيف، أي محتوى الرطوبة، من 47٪ إلى 9٪ للفول السوداني، وبالنسبة للفلفل الأحمر، انخفض محتوى الرطوبة من 90٪ إلى التوازن خلال 5 ساعات كذلك.

الكلمات المفتاحية: المجفف الشمسي؛ المركز المكافئ؛ حركية التجفيف؛ الأساس الرطب؛ نظام التتبع.

Table of Contents

List of figures

List of tables

List of annexes

Notations and Abbreviations

ISDPSDC	Indirect Solar Dryer using parabolic solar dish concentrator
USA	United States of America
m	Meter
mm	millimeter
h	Hour
W	Watt
°C	Celsius
IH	Initial humidity
FH	Final humidity
ANN	Artificial neural network
SVM	Support vector Machine
PTC	Parabolic-trough solar concentrating systems
MR	Moisture ratio
Me	Moisture content
Mi	Initial moisture content
t	time
RH	Relative humidity

General Introduction

Nowadays, discussions on global warming, energy security, depletion of fossil fuels at a higher rate and economic growth call for a more sustainable development to reduce the energy usage and pollution rates in different sectors [1]. In the recent years, attempts for alternative energy sources are developed to preserve agriculture products by drying technics. As best alternatives to achieve this is to utilize solar energy since it is environmentally friendly, clean, renewable, and usable for the entire day [2].

Drying is one of the most efficient ways of preserving agricultural production, marine products and medicinal plants by reducing its water activity, a lower water activity inhibits the growth of spoilage causing microorganisms and also the enzymatic activity that favors the degeneration of these products [3]. Solar dryers are generally classified as direct, in which the drying process involves in a simultaneous supply of energy by the sun in the open area for mass and heat transfer operation. While the second type is indirect drying mode, the main point in this type is to make air circulation through the dryer for providing either natural or forced convection [4].

The direct drying is widely used by agriculturalists but has practical constraints, such as high products losses caused by insufficient drying; violation of insects; animals and fungal attacks, unpredicted rains; and other effects of climate conditions. Moreover, open sun drying does not enable sufficient management and control of the system and leads to production losses and degradation of product quality [5]. In order to avoid the mentioned limitations of direct drying and to improve the quality of the dried products, indirect solar dryer became increasingly used for crop drying. However, this type of drying needs more theoretical and experimental researches to understand the various exist technologies and their parameters to reach the required performances and innovative solutions at industrial scale. The major issues of indirect solar drying design concept are to make it adaptable to different kind of environment. Therefore, due to climate variation, the adoption of solar drying system is limited to the periods at which condition is favorable. To success in dealing this problem, various studies have tested different design strategies to make solar dryers applicable and permanent in unstable weather conditions [6, 7].

The specific objective of this thesis is to test indirect solar dryer assisted by parabolic solar dish concentrator for improving its performances. The role of parabolic solar dish concentrator is to get high temperature in the drying chamber without using external source such as electrical resistance or heater gas. The experiments were carried out during the wind period when the weather was volatile. This situation limited the opportunity of natural drying so that forced dryers are often the main solution for drying agro-food products. The proposed solution in this study leads to enhance two criteria for the role of parabolic solar dish concentrator as indirect solar dryer which are the air temperature and drying time [8].

The present thesis is divided into five distinct chapters. The first chapter includes a bibliographic research about drying technologies, of course with a brief presentation of solar potential of El oued region.

Second chapter provides a literature review on enhancement techniques for solar dryer performances. Whereas the third chapter will present a realization of different indirect solar dryer models for performance enhancement, which are an indirect Solar dryer with the integration of local and waste materials for heat storage, indirect Solar dryer assisted by Parabolic-trough solar concentrating systems and indirect Solar dryer assisted by parabolic solar dish concentrator.

The fourth chapter presents an experimental investigation of the thermal performance of different indirect solar dryer models. In addition to that a comparing results by mathematical models of solar drying in thin layers will take place in this chapter.

Finally and as last section, the conclusions of this thesis and recommendations for the future work are exhibited.

Drying technologies

I.1 Introduction

Removing water (or drying) is a simple process of excess water removal from a natural or industrial product in order to reach the safe storage. It is an energy-consuming process. It is very important to lower the agricultural products to be stored moisture content, As the moisture content of agricultural products in between (25%-80%). Dehumidification of agricultural products slows down the action of enzymes, bacteria, yeasts and molds. We can dry from keeping the products for longer without damage [9].

The most widespread method of drying is convection drying (hot air is passed over the material to be dried), The passage of hot air is over the product, under the product, or both, or through it where it is perpendicular to it [10].

Its preservation processes by drying have serval advantages, we mention them:

- Drying preservation is one of the most commonly used preservation methods for low costs and no need for storage inside specially equipped stores as refrigerators.
- The relative decrease of dried materials due to the decrease in the expenses of their manufacture and the absence of the need to use raw materials that increase in value.
- The low weight and size of dried products help in their transport and storage.
- Retain food when it is scarce and thus regulate supply and demand processes.

I.2 A brief history of drying

Drying has been conducted since time immemorial with the main purpose of preserving food and agricultural produce. Solar Drying by exposing products to sunlight is one of the most important uses of solar energy in past eras. Humans in earlier decades used drying in order to store vegetables, fruits, fish and meat. It is also used in pottery and construction bricks….

It recounts that when it was Nearchus, the admiral of Alexander the Great, was sailing with his fleet across the Macran Coast (now the border between Iran and Pakistan), they arrived in a place called “Mahi Khoren” which in Persian means fish-eaters (ichthiophagi). In the bread and cake industry, they relied on drying large fish and mixing them with flour. This technique is used today in the said area [11].

Around 8000 BC the first drying facility was discovered in the south of France. It was a surface studded with stones and used for drying out in agricultural crops [12].

Several drying facilities are found in different regions of the world between the years 7000 and 3000 BC. There were many built-in installations for drying agricultural product in particular. In Mesopotamia dryers are found for drying written clay tablets [13].

The Greek philosopher and physician Aristotle described the phenomenon of drying and explained it with theoretical explanations of the first time [12].

The selected drying technologies discussed in the literatures are: freeze drying, spray drying, fluidized-bed drying, and supercritical drying. Spray drying is probably the most mature alternative technology to freeze drying and can be applied to the production of many pharmaceutical products.

Later several methods of drying were used, such as biomasses, wood, fuel and electricity, however, are expensive compared to free solar power and environ mentally friendly [12].

I.3 Drying Definition

The drying process in is aimed at partially or completely removing water from the body by evaporating this water. this process involves heat transfer and move the mass (the liquid impregnating the solid passes to the vapor state in the drying air) [14].

Drying is widely used in the chemical and food industries where it is often that complement processes such as sedimentation, filtration or dewatering. The classification of drying causes are as follow [15] :

- Facilitate the preservation of products (by reducing water activity) and mitigate the seasonal nature of some agricultural or industrial activities.
- Reduce the mass and volume of products to reduce their size and facilitate their transport.

- Give a particular presentation or functionality of the product (chips of potatoes, freeze-dried coffee, etc.).

I.4 Drying processes: Several processes are involved, namely

I.4.1 Heat pump drying

Heat pump dryers and dehumidification dryers rely only on electricity. As shown in Figure I.1, this type of dryer is fitted with a refrigeration unit consisting of cold battery, evaporator, hot battery, and condenser [16].

The heat pump produces more energy than it uses. Heat pump dryers are manufactured in two ways:

- Closed circuit: there is no air exchange with the outside;
- Open circuit: an air exchange with the outside is performed to reduce the temperature in the dryer.

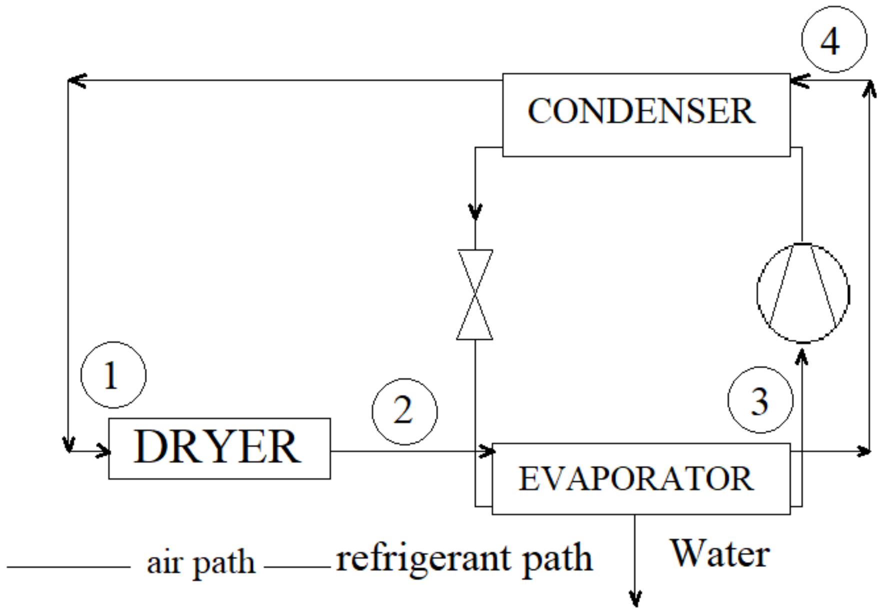


Figure I. 1 Schematic of heat pump drying system [17].

I.4.2 Drying with hot air conditioning

This is the most typical procedure. It, in particular, enables working across a wide temperature range up to 90°C. The dryer's humidity is removed by exchanging air with the outdoors. Heat can be delivered directly by a burner or indirectly using heating batteries filled with hot water, steam, or any other thermal fluid [16].

I.4.3 Vacuum drying

Vacuum drying can be a useful tool for solid products that are heat-sensitive. A vacuum dryer is an airtight enclosure in which the pressure is reduced using a vacuum pump. It is the combined actions of pressure and temperature that will accelerate the circulation of water in the products and intensify evaporation. The decrease in pressure favors the circulation of water from the core to the surface. In the case of wood for example, water circulates five times faster in the material under a low pressure of 60 mmHg, than under a normal pressure of 760 mmHg, [18].

It is this property that is used in this vacuum drying process: the main characteristic of vacuum drying is its speed (3 to 6 times faster than air-conditioned hot air drying). This type of drying is more suitable for large quantities [16].

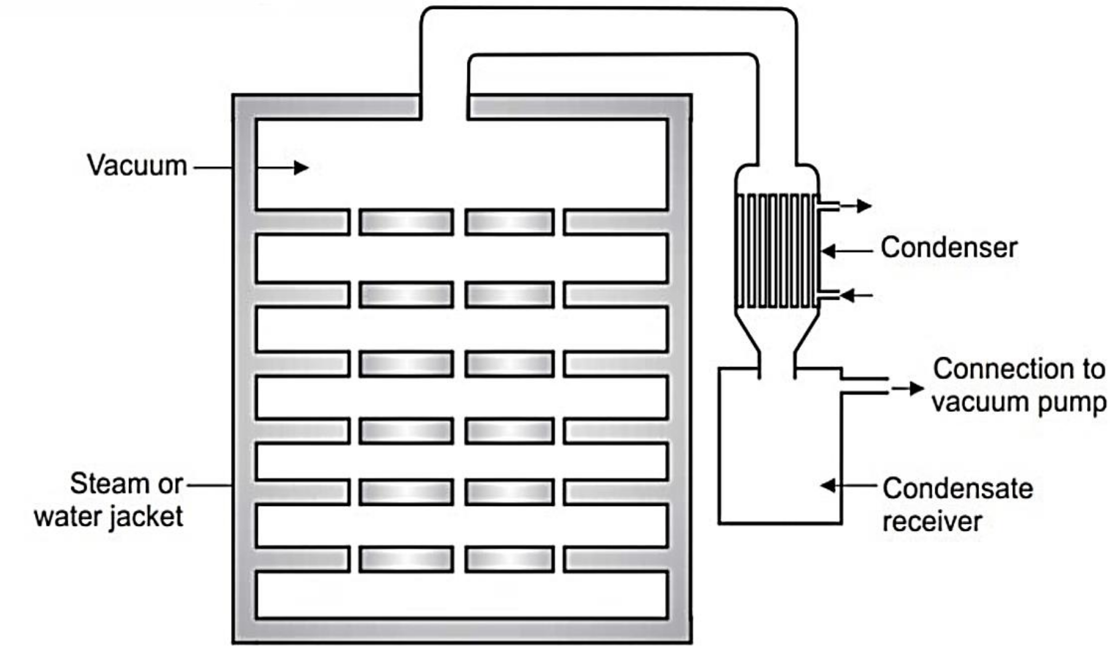


Figure I. 2 Vacuum dryer

I.4.4 Pre-drying

Pre-drying is the process of artificially drying a product until it reaches a certain humidity level. Pre-dried items can be delivered to drying cells to achieve the required final humidity level, depending on the demands of the user. Because of the gentle and regulated drying, this approach increases product quality [16].

I.5 Drying modes

I.5.1 Open air drying

The oldest technique is open-air drying or natural drying (also known as traditional drying), which is accomplished by keeping the goods to be dried in well-ventilated shelters that are suitably spaced apart to enable excellent air circulation. In arid and dry places, this drying procedure, which requires no artificial heat source, remains relatively efficient. It is appropriate for modest productions for self-consumption or local consumption. Its benefit is that its material costs are relatively low, but its downside is that the items stay exposed to the open air, exposing them to dust, insects, and mold growth owing to the reintroduction of dust humidity overnight. Furthermore, because drying pace is strongly related to weather conditions, managing the time of drying and the quality of the items to be dried becomes difficult, if not impossible. To mitigate these disadvantages, the items can be protected beneath a structure or covered with waterproof canvas at night or when it rains. To encourage air circulation and ensure equal drying of all the goods, agitate the items periodically during drying on racks that are not overcrowded with products.

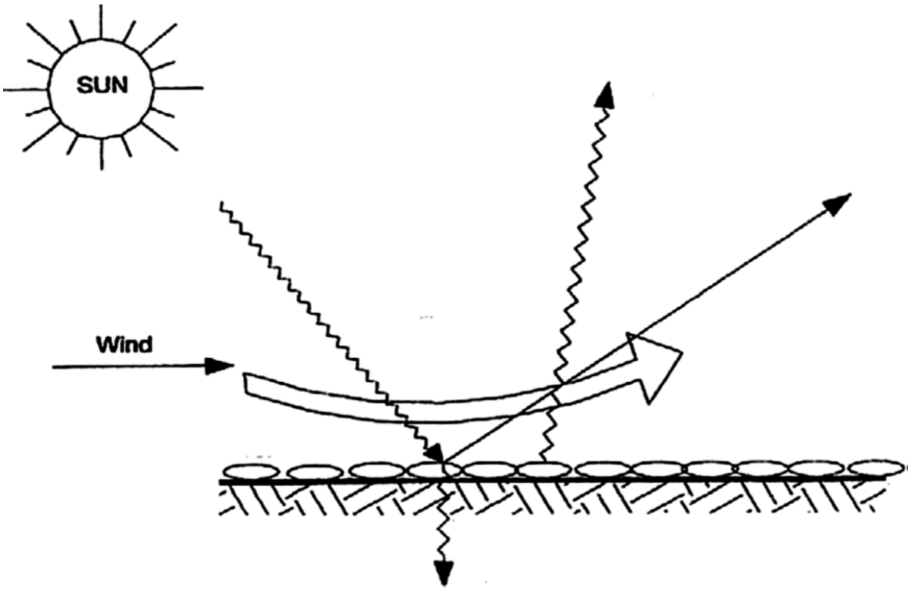


Figure I. 3 Open air drying [19].

I.5.2 Solar drying

Solar drying is a form of drying that falls between artificial and natural drying. This drying process achieves a lower end humidity than air drying but a substantially greater humidity than artificial drying. The drying parameters are more exact than with air drying but less precise than with artificial drying [20].

The source of energy is the sun which emits solar rays whose wavelengths are essentially between 0.25 µm and 2.5 µm. These photons are subsequently converted into heat by the absorber, which then transmits infrared radiation [21].

The **Table I. 1** below lists the main advantages and disadvantages of solar drying and open air drying [22].

Table I. 1 Advantages and disadvantages of solar drying and open-air drying

	Solar drying	Open air drying
Advantages	▪ Control of the desired final water content. ▪ Obtaining a quality product (less losses). ▪ Source of energy « Free ». ▪ Allows the management of the drying line. ▪ No risk of attack by insects or fungi. ▪ Low to medium cost.	▪ Gentle drying, thanks to the day/night alternation. ▪ No qualified personnel required. ▪ Low humidity gradient in the thickness. ▪ Little color change. ▪ No energy expenditure. ▪ Source of energy « Free ».
Disadvantages	▪ Significant initial investment. ▪ Power consumption. ▪ Operation of the dryer.	▪ Slow drying, (response time to the penalizing market). ▪ Significant losses due to drying defects. ▪ Large occupied surface. ▪ Risk of attack. ▪ Difficulty reaching the desired water content.

I.5.2.1 The direct solar dryer

Direct solar drying is a simple concept that utilizes direct sunlight to dry vegetables. It is easy to create. They are typically basic and sturdy constructions with a glass frame that is utilized to maximize the greenhouse effect.

Due to the simplicity of the models, air circulates through the dryer by natural draft caused by heating (chimney effect), wind impact on the apertures, or using a fan [16].

This type of drying has two advantages:

- The products are better protected from the attack of flies and other insects.
- They are susceptible to the same greenhouse effect as a flat collector absorber, resulting in an improvement in the radiative balance and an increase in the temperature of the product to be dried, allowing for much shorter drying durations as compared to standard systems.

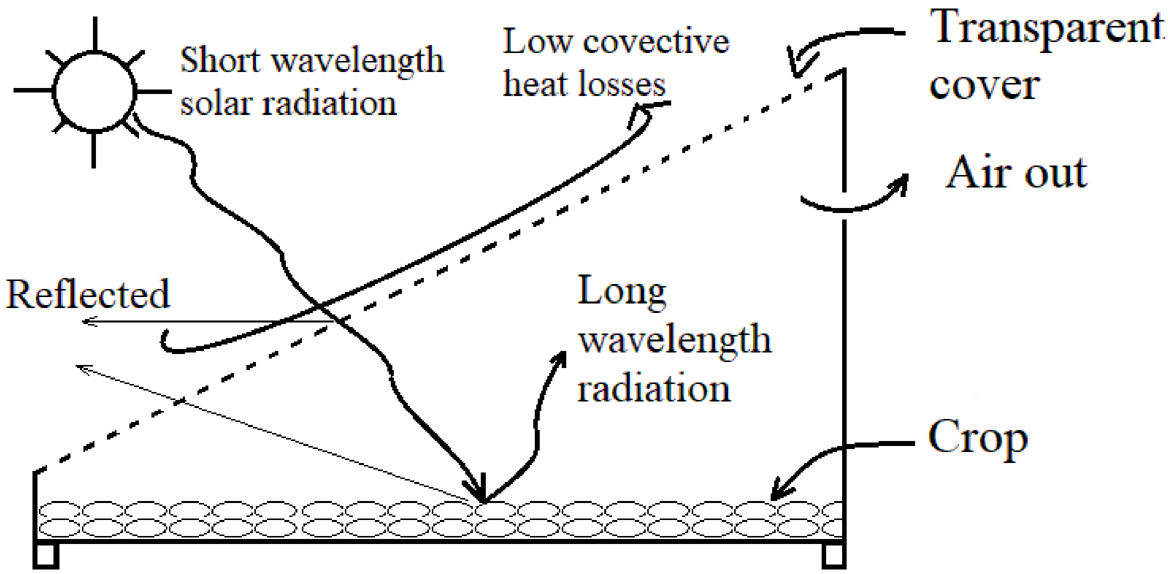


Figure I. 4 Direct solar dryer [23].

I.5.2.2 The indirect solar dryer

In indirect solar dryers, the radiation does not reach the products to be dried directly. The air is first heated in a solar collector, consisting of a glazed surface located above and an absorbent surface, usually painted black, then led into the drying chamber to dry the product. The solar collector is generally a separate module that attaches to the drying chamber during exposure to the sun and whose inclination aims to maximize the collection of solar energy [23].

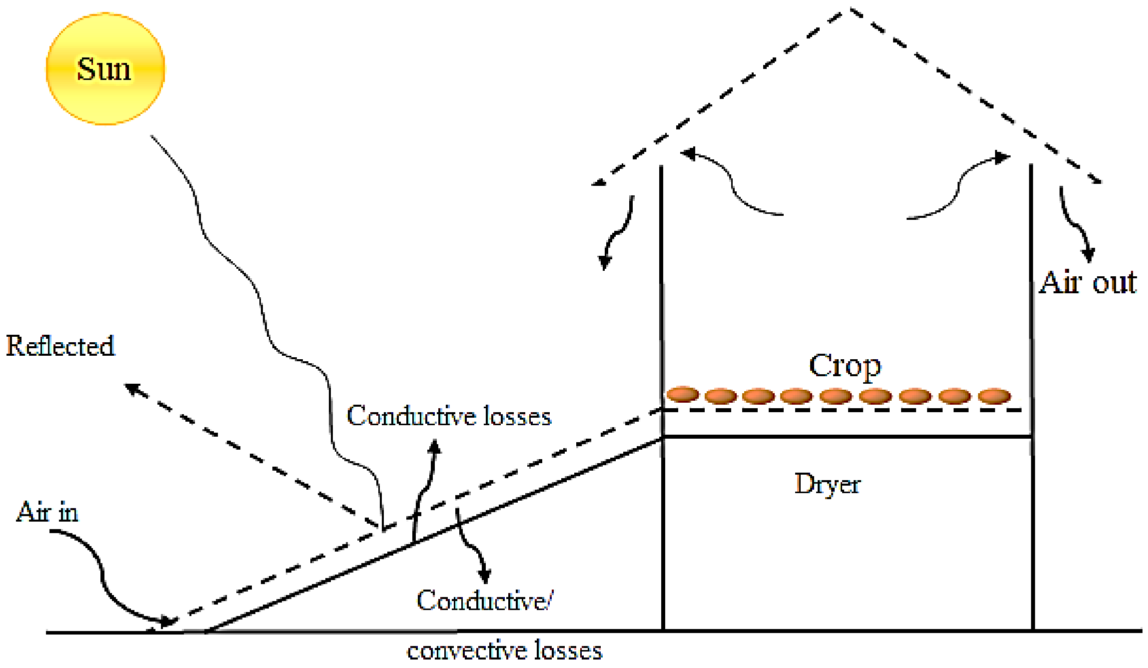


Figure I. 5 Indirect solar dryer [23].

I.5.2.3 Mixed dryers

The heat necessary for drying is given by the combined action of solar radiation impacting the items directly and warmed air in collectors in this type of dryer. [24].

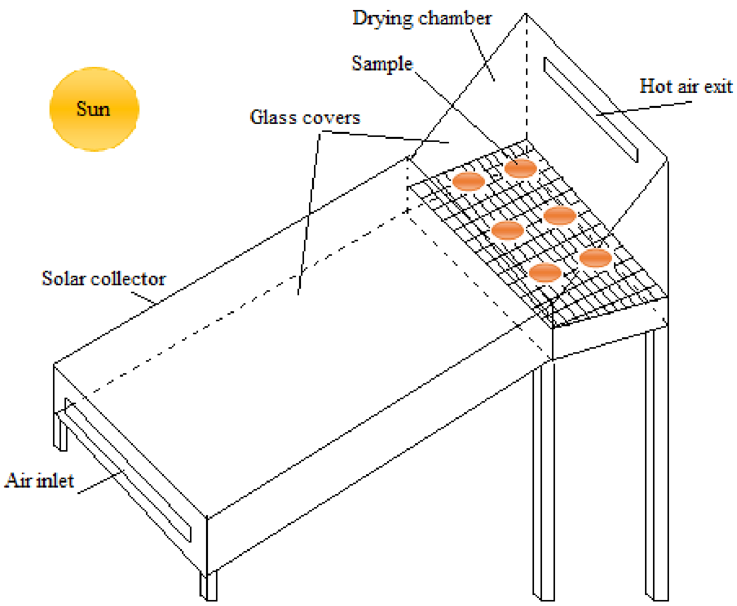


Figure I. 6 Mixed-mode solar dryer [19].

I.5.2.4 Hybrid dryers

These dryers use, in addition to solar energy, additional energy (fuel oil, electricity, wood, etc.) to ensure a high level of air heating or to ensure ventilation. Solar energy is often used in this case to preheat the air. These more expensive systems are generally reserved for large-scale applications, or for commercial applications for which the quality and flow rate of the finished product cannot depend on climatic conditions.

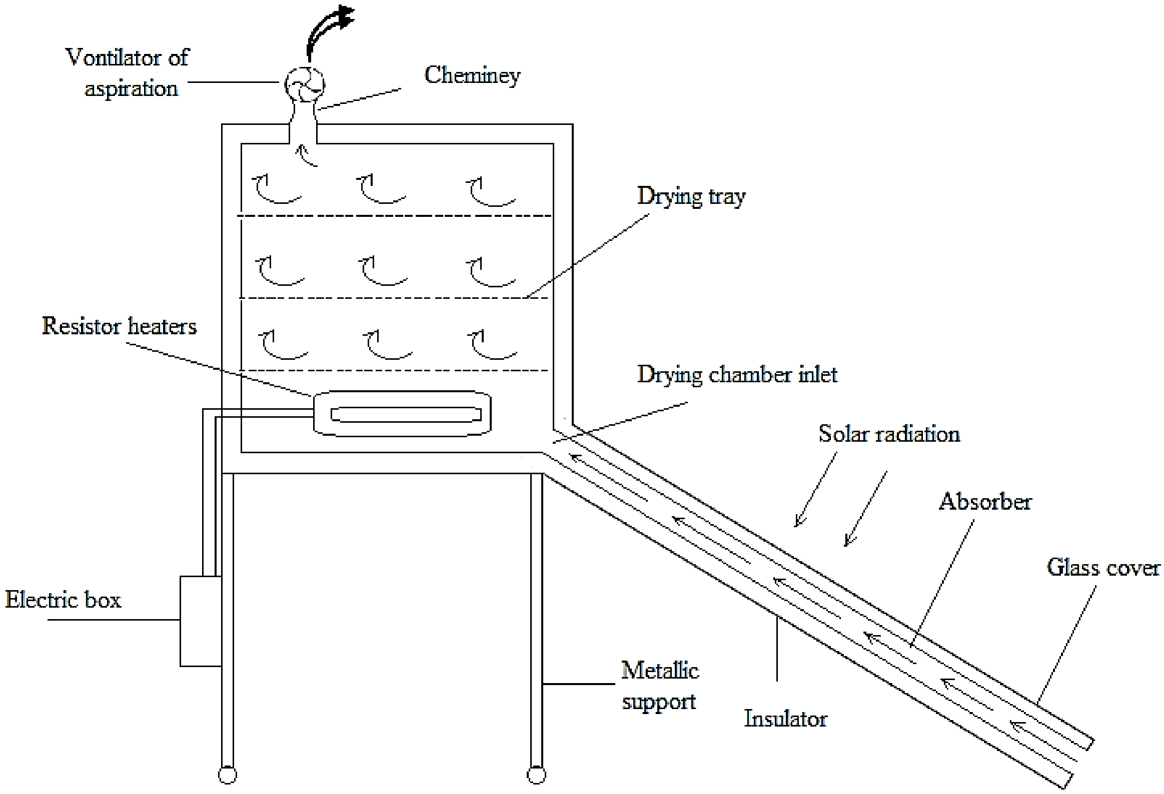


Figure I. 7 Hybrid dryers

I.5.3 Type of solar dryer

Solar dryers use the heat from sun to remove the moisture content of food substances. There are two general types of solar dryers: Direct and indirect.

I.5.3.1 Direct effect dryers

Direct solar dryers expose the substance to be dehydrated to direct sunlight. Historically, there are several types of direct dryers.

I.5.3.1.1 Sharma Dryer

This dryer, with a capacity of 7.1 m3 of wood, was tested in India in 1972. Since then, more than twenty have been in operation at latitudes varying from 17° to 30°N. With the exception of the north wall, which is insulated, all the other walls and the roof are constructed of 5.5 mm thick double glazing enclosing a 37 mm air space. A corrugated absorber is placed horizontally above the wood pile. Air circulation is provided by two of 1 KW power fans, placed on the side of the north wall. The air inlet and outlet are made through openings placed respectively in the south wall and the north wall. The drying time recorded with this dryer is 4 times less than that in the open air [25].

The regulation of the dryer is done manually and is limited to:

- A maximum value of the relative humidity of the air above which the valves are opened (for wood humidity above 40%, the dryer operates in open mode allowing it to be supplied with dry air, in order to promote water evaporation, for humidity below 40%, the dryer operates in closed mode since the rate of drying at this stage depends more on the air temperature).
- A minimum temperature value below which drying stops.

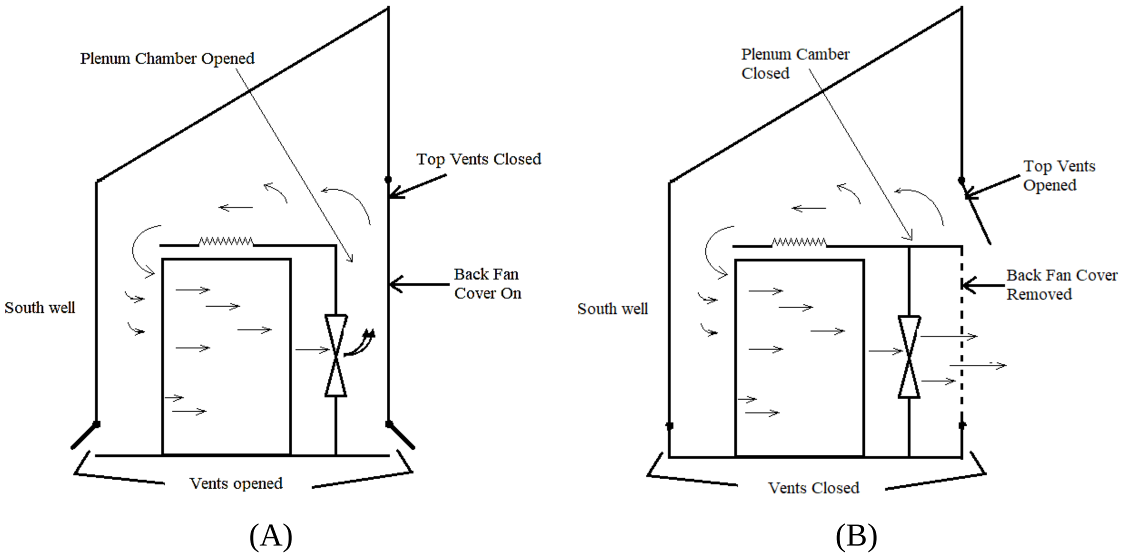


Figure I. 8 Sharma dryer with open (B) and closed (A) mode

I.5.3.1.2 Prestemon Dryer

It has 2.4 m^3 of capacity. This dryer was built in 1983 in Ames, USA (Latitude 42°N, longitude 94°W). With the exception of the roof, all sides of the dryer are made of a layer of chipboard, fiberglass and structural wood; all internal surfaces are painted black. The roof that plays the role of the sensor is made of a layer of polyester and fiberglass. Air circulation inside the dryer is ensured by two 50 cm diameter fans placed near the roof. The air exchange with the outside is done by six perforated openings in the north wall. The drying time for 25 mm hardwood was 4 weeks in the summer season with a final humidity of 7 to 8% [26].

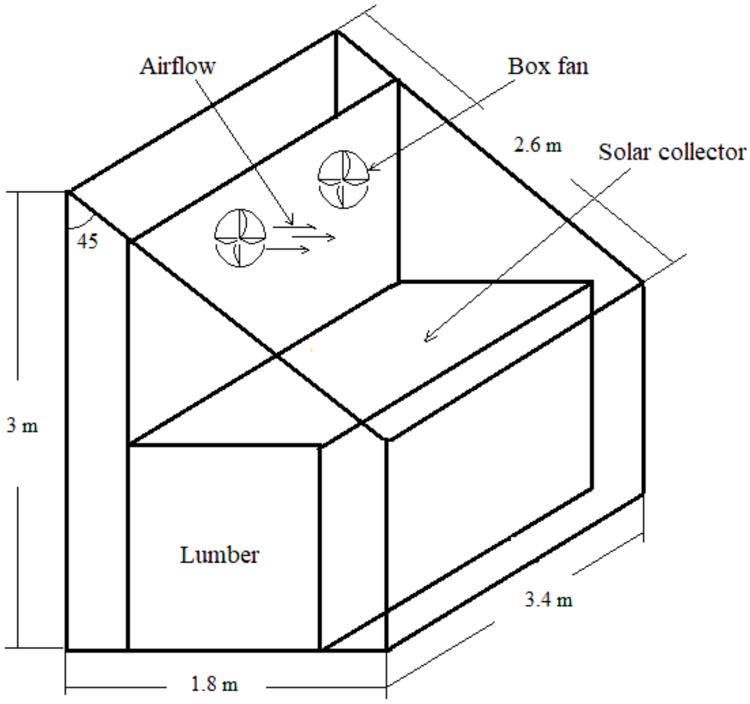


Figure I. 9 Prestemon solar dryer [27]

I.5.3.1.3 Solar Tunnel Dryer "Hohenheim"

This dryer is mostly used in the food industry. It is created in partnership with Germany's Hohenheim University and INNOTECH Engineering. It is primarily meant for tropical and subtropical regions and is commercially available in over sixty countries worldwide.

The solar cells in the Tunnel drier power the fans, which circulate the air in the drying zone. The fan significantly lowers drying time. The air circulates through a black-painted region (collection area) to absorb the heat of the sun and then through the trays containing the items to be dried. Some dryers are complemented by the addition of a chimney for better air circulation, or by the use of an external heating system such as hot water to guarantee more efficient drying during the night, or when weather conditions are unfavorable [28].

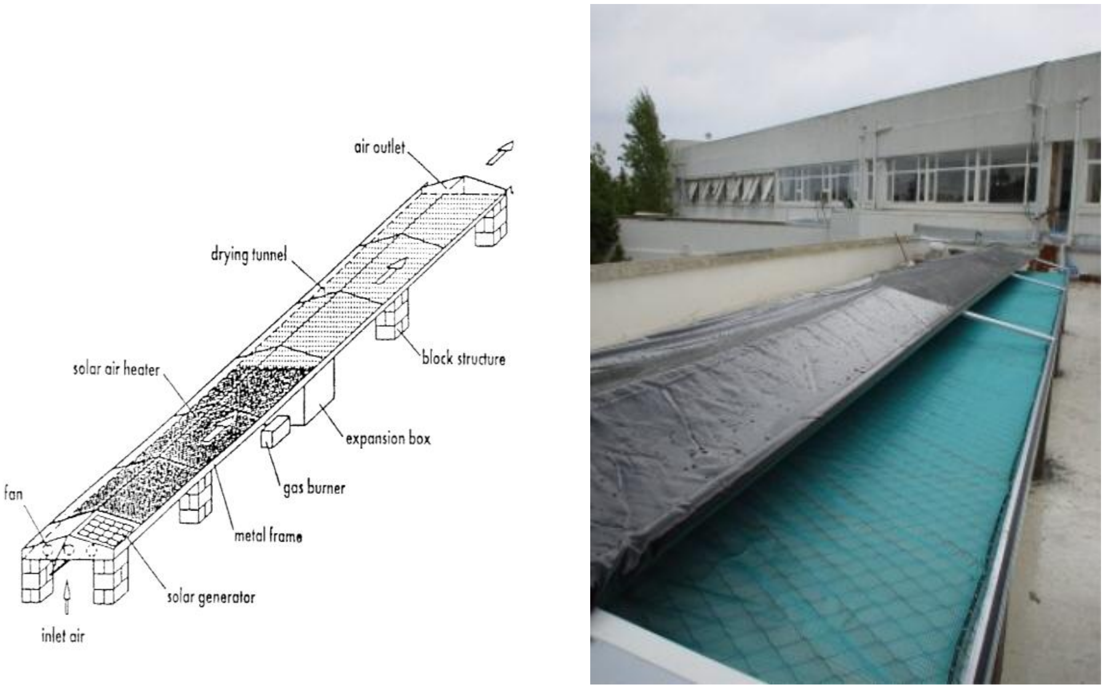


Figure I. 10 Plan of a tunnel solar dryer

The technical data of the tunnel dryer are summarized in the following Table I. 2

Table I. 2 Technical characteristics of the INNOTECH Tunnel dryer Engineers gesellschaft [16].

Length	18 m
Width	2 m
Surface	16 m2
Drying area	20 m2
Air flow	400 à 1200 m3/h
Air temperature	30 à 80 °C
Power required	20 à 40 W
Fan operation	Photovoltaic solar panel

I.5.3.1.4 "Twaalf Ambachten" drayes

Figure I. 11 illustrated a dryer of this sort. It was created for food goods by a Dutch organization that invests in the development and dissemination of alternative technological and ecological solutions.

The dryer assembly is tailored to the climatic conditions of northern Europe, taking into account an angle of inclination of 58° established by the typical position of the sun in spring, summer, and early fall. The solar dryer is designed in such a manner that the rays cannot directly reach the product contents. Convection and radiant heat from the black painted aluminum plates positioned behind the glass, which also serves as a support for the racks, heat the air. A 10 cm aperture at the box's top allows hot air to enter. A barrier with a 10cm aperture on the rear wall opposite the glass is used to suck damp, cool air out of the box via the flue pipe at the top of the box. The chimney flue is around one meter in length. The interior black tube is separated from the Plexiglas tube. The box is made of concrete-plex and sits on a moveable table. The larger stand at the bottom is 100cm x 110cm, and the smaller stand at the top is 55cm x 110cm.

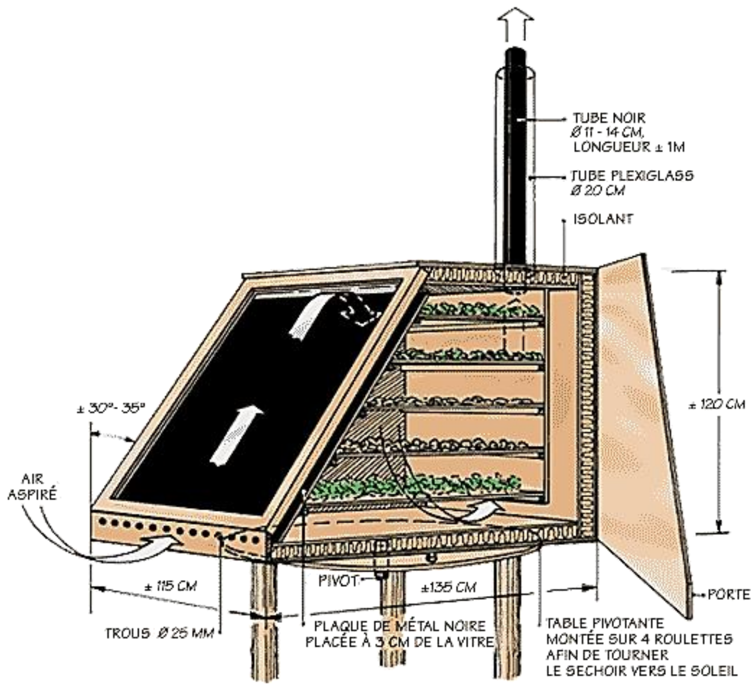


Figure I. 11 Twaalf Ambachten dryer [16]

I.5.3.2 Indirect solar dryers

As with artificial dryers, the items are put in an insulated chamber for this sort of drier. Because the solar collectors are isolated from the drying chamber, the collecting surface may be optimized without being constrained by the size of the drying chamber. Heat is transferred between the collectors and the drying chamber through insulated pipes. This type of dryer provides for improved drying chamber insulation, reducing heat losses [29].

I.5.3.2.1 Dryer of Simpson et al.

This dryer was built in 1984 for drying wood in the Philippines (14° 34' 59.99" N, longitude of 121° 00' 0.00" E) with a capacity of 9.4 m^3 of wood. The frame of the drying chamber is made of wood, the walls and the ceiling have a heat transfer coefficient of 0.347 and 0.207 $W.m^{-2}. K^{-1}$ respectively. The sensor is oriented towards the south and placed at ground level, the transparent part is made of 10 mm thick fiberglass. The absorber provides good thermal insulation at floor level. Hot air is introduced into the drying chamber when the temperature of the sensor is higher than that of the chamber.

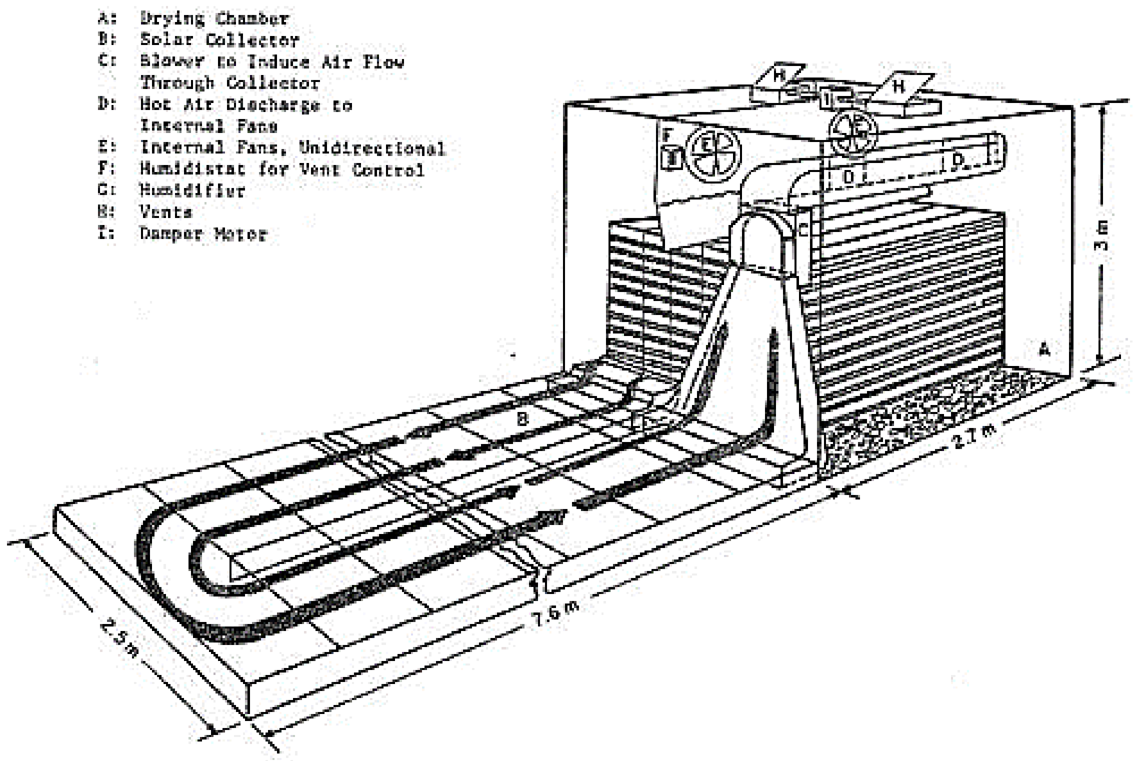


Figure I. 12 Dryer model of Simpson et al [30]

I.5.3.2.2 Lumley and Choong dryer

This dryer has a capacity of 0.9 m^3, it was built in 1981 in the USA. The solar collector is placed above the drying chamber built in chipboard and insulated. Air circulation is provided by a 0.6 m diameter fan. The passage of hot air from the collector to the dryer is stopped during the night [31].

Table I. 3 Performance of the solar dryer of Lumley and Choong [32].

Wood	Thickness (mm)	Humidity (%)	Drying time (days)
Ash	31	51-14	19
red oak	38	82-17	29
Cypress	25	88-10	21

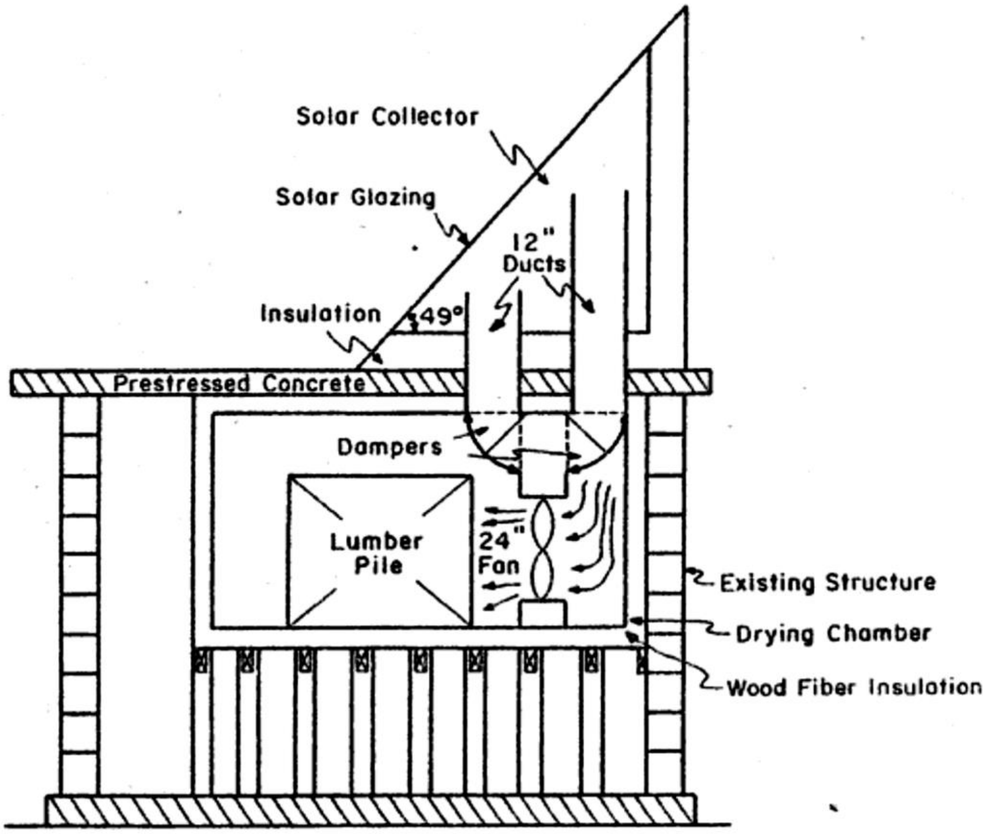


Figure I. 13 Solar dryer of Lumley and Choong [33]

I.5.3.2.3 ICARO Dryer

This dryer type is a type of solar dryer that uses indirect light and forced ventilation. These versions are distinguished by the fact that the forced ventilation energy is provided by a solar panel, making the unit totally self-sufficient in terms of energy. This sort of dryer's products is agri-food in nature

The Icaro 1.5 model is made of sheet metal that measures 2.44 m x 1.22 m. The Icaro type dryers have been researched so that they may be built in Africa by artisans using locally accessible materials, as well as a building process tailored to moderately equipped metal carpentry workshops [34].

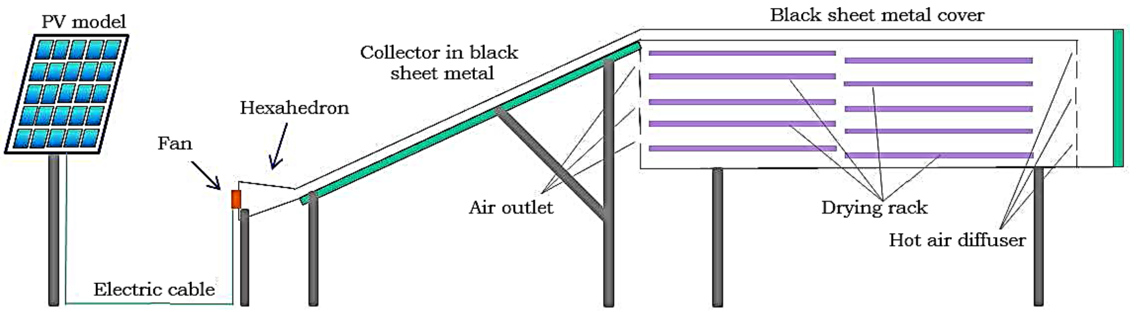


Figure I. 14 ICARO model 1.5, 2007 [35].

This type of drier dries agricultural and culinary goods (meat, medicinal herbs, fruit and vegetables).

The Icaro dryer covers a number of requirements to ensure excellent drying:

- Drying away from the sun to have a product color that is brighter and more similar to that of the fresh product and a high vitamin content;
- Forced ventilation to have a very good chance of drying success by having a high capacity for the expulsion of humidity;
- Complete energy self-sufficiency;
- Absence of glass due to its cost and fragility. Reflective surfaces have been adopted to achieve the desired temperatures and correct drying;
- Possibility of moving the unit to the production sites and using them on site in order;
- Simplicity of realization;
- Ease of use;
- Good drying ability;
- Moderate price

I.6 Relevant state variables affecting solar drying

Solar drying is governed by energy and heat exchanges between the product and its surroundings. Taking these elements into account allows for the creation of models that precisely reflect the behavior of solar dryers as well as the evolution of water in the product to be dried [22]. These are the variables:

I.6.1 Temperature

This variable is represented by three quantities: the dry bulb temperature, the wet bulb temperature and the dew temperature. The dry bulb temperature corresponds to the air temperature. When drying the product such as wood, the evaporation of water absorbs heat causing the air to cool. We then find the concept of the wet bulb temperature corresponding to the temperature of evaporation of water on the surface in the first phase of drying. Another important quantity when studying moist air is the dew point temperature. It corresponds to the temperature at which the water vapor contained in the air condenses on colder surfaces.

The dry bulb temperature is the drying air temperature. It follows a diurnal oscillation, and its amplitude varies according to season: it is stronger in continental regions than in coastal regions, it decreases with latitude, and it increases in the case of a highly gloomy sky.

The drying rate is largely influenced by the air temperature. This effect is caused by the heat input to the product, which increases as the air temperature rises. It is also attributable to the product's temperature, which is especially essential given the high temperature of the air. As a result, the rate of water diffusion in the product increases with temperature.

I.6.2 Air humidity

The ratio of the partial pressure Pv to the saturation vapor pressure, Pv-sat, is represented by this state variable. When the air is saturated, the relative humidity of the air is 100%.

Absolute humidity, as opposed to relative humidity, relates to the amount of water vapor contained by 1 kilogram of dry air and is represented as kg of water vapor per kg of dry air.

It is critical during the drying process to be able to estimate the humidity contained in the air within the solar dryer, track its progress, and know how to adjust its level.

The water content of the air has a significant impact on the drying kinetics of the goods to be dried. This impact, like air velocity, is larger at the start of drying and reduces as air temperature rises.

Experiments reveal that humidity flows perpendicular to surfaces of equal humidity from a humid zone to a dry region.

As an example of wet-to-dry wood, the temperature gradient opposes the moisture gradient. In the heart of the wood, the humidity is higher than at the surface, while the temperature is higher at the surface than at the level of the heart.

Based on these data, drying will be accelerated if the center of the wood is warmer and more humid than the periphery [36].

I.6.3 Pressure

As previously stated, moist air is composed of a combination of dry air and water vapor. The moist air mixed pressure is just the sum of the partial pressures of dry air Pa and water vapor Pv. The saturation vapor pressure, Pv-sat, is used when the air contains the most water vapor at a certain temperature. At the surface temperature, the vapor adjacent to the product's drying surface is at saturation vapor pressure (in the first phase of drying).

One of the driving forces favoring the evaporation of water from the product is the difference between these two pressures, which is known as evaporative power.

I.6.4 Air speed

The displacement of an air mass caused by the force of the pressure gradient is described as air velocity (high pressures towards low pressures).

When temperature and relative humidity are constant, drying is sped up by increasing air velocity at the product's surface. Low evaporation is caused by low air velocity. Indeed, if there is no movement surrounding the product, a layer of saturated air will form, preventing humidity exchange from the product to the air [18].

In fact, when it comes to eliminating free water, air speed has a strong impact at the start of the drying process, but it has less influence at the end. As a result, having variable speed fans in some circumstances, with the option of high speed at the start of drying and a lower speed towards the conclusion of drying, leads to energy savings with drying efficiency.

I.7 Examples of thermal characteristics of solar dryers

An efficient solar dryer is a dryer that allows rapid drying without degradation of the products to be dried. This kind of dryers depends on the meteorological conditions which consequently influence the variables inside the dryers (temperatures and humidity) which are able to optimize the criteria of appreciation of the drying. The choice of the product to be dried must therefore be adapted to be dried in the dryers representing the best conditions.

Air containing a certain amount of water, at low temperature, will, when heated, have a greater water-holding capacity. The **Table I. 4** below gives an example of air at 29°C with a relative humidity of 90%. This air, when heated to 50°C, will then have a humidity of only 15%. This means that instead of being able to absorb only 0.6 g of additional water per kilogram (at 29°C), it is able to absorb 24 g per kilogram at (50°C). Its moisture absorption capacity was therefore increased, because it was heated.

Table I. 4 Absolute humidity as a function of temperature and relative humidity (solar drying, practical action).

Air temperature in °C	Relative humidity in %	Quantity of water in grams per kg of dry air necessary to obtain a relative humidity of 100%
29	90	0.6
30	50	7.0
40	28	14.5
50	15	24.0

I.7.1 Case of drying of agri-food products

In the case of food products, when placed in a stream of heated air, they first lose moisture from their surface. As drying continues, the moisture contained within the food material then evaporates, starting with the areas closest to the outer surface. The ability to dehumidify becomes more and more complex as it approaches the core of the material and moves away from its surface. Eventually, it is possible to no longer be able to remove more moisture, and the food is then in equilibrium with the drying air.

The best condition for drying crops in a short time is when the air is dry and warm. If the air is hot, then less air is needed. The temperature of this air will mainly depend on the temperature of the surrounding air, but also on the amount of solar radiation directly received by the food to be dried [37].

I.7.2 Wood drying case

For the case of wood as a product [38], certain types of species have the ability to dry faster than others. Thus, softwoods such as beech dry faster than hardwoods such as oak and Kotibé. Table I. 5 presents different types of wood with different thicknesses and different initial humidity in the two cases of drying by solar dryer and drying in the open air. Solar drying considerably reduces drying time for all species [39].

Table I. 5 Drying time in dryers and in the open air depending on the species.

Author	Essence	Thickness (mm)	Solar drying			Drying in the open air		
			IH	FH	Time	IH	FH	Time
Chen	Yellow Poplar	27	106	15	27	105	15	168
Gough	Cypress pine	25	39	12	36	39	15	54
Read	E.delegatensis	25	100	15	20	100	42	20
Simpson	Acer platonoîde	29	67	8	26	67	20	40
Steinman	Pinus radiata	25	93	12	15	93	23	16

I.8 Climatic characteristics of the region of Eloued

The climatic characteristics of the region where the solar dryer will be installed contribute considerably to its performance. Indeed, the control of the evolution and the variability of the meteorological parameters of the site will allow to have a global and clear view on the optimal periods of drying.

The climate expresses the combination of its consecutive elements (Precipitation, Temperatures, Humidity, Wind, Pressure, Sunshine, etc.). Knowledge of the climate involves the ability to describe the average conditions of meteorological parameters, but also occurrences of phenomena such as heat and cold waves, droughts, intense rains, storms, etc., as well as the statistical parameters characterizing the deviations from average conditions.

The climate variability and change that has affected the weather and climate in recent years is becoming more and more remarkable by the frequency of extreme events and the change in observed weather conditions of the climate, especially for the parameters related to temperature and precipitation. that have a direct impact on socio-economic sectors. This is why a climatic analysis integrating all past and future statistical information makes it possible to understand and identify the climatic characteristics of the region [40].

Literature Review on Enhancement Techniques for Solar Dryer Performances

II.1 Introduction

Increased understanding of renewable energy plays a critical role in improving technology for farmers worldwide, particularly in emerging nations like India looking to enhance agricultural productivity. Poor storage, processing, and marketing facilities in many developing countries in the Asia pacific resulted in about 40% of waste. Although India is a large producer of several horticulture plants, many Indian farmers are still unable to meet their daily demands for vegetables and fruits, resulting in a very low human development index. Due to a lack of effective post-production/harvest processing, vegetables and fruits cultivated in India are damaged. This results in a significant disparity between overall food output and actual availability after harvesting. Reducing post-harvest losses is critical for increasing the availability of food from an existing product. Traditional techniques of food preservation include canning or bottling, freezing, salting, sugaring, and drying [41].

II.2 Solar dryer

The design of the solar dryer was separated into two key components: the air collector and the main storage cabinet. Air collector cabinet was inclined with surface and ground as depicted in Erreur ! Source du renvoi introuvable.**Figure II-1**. The degree of inclination of the air collector was designed to gain optimal exposure to sunlight throughout the day. The ideal tilt angle of a solar collector may be calculated by multiplying the location latitude by 0.9 and then adding 29 [42, 43].

Figure II-1 Solar Dryer

II.3 Open sun dryer

As shown in **Figure II-2** open sun drying is the simplest way of drying agricultural goods that has been used since ancient times, in which agricultural items that need to be dried are sprayed in the sun light on plastic, metal sheets, or direct ground. The sun is an uncontrollable source of energy, and its strength varies depending on the weather. The majority of the radiating energy on the surface of the sheet is reflected, and the quantity of heat absorbed by radiation is responsible for rising product temperatures. In the event of an open space, a lot of heat is lost to the surrounding environment, resulting in inefficient use of solar energy. It cannot achieve crop/product standards due to the drawbacks of decline in crop quality. The open sun drying method likewise takes a long time to dry a product. Other constraints include agricultural deterioration owing to dust, soil, climate change such as rainfall, birds, and the requirement for extra area for product distribution [44].

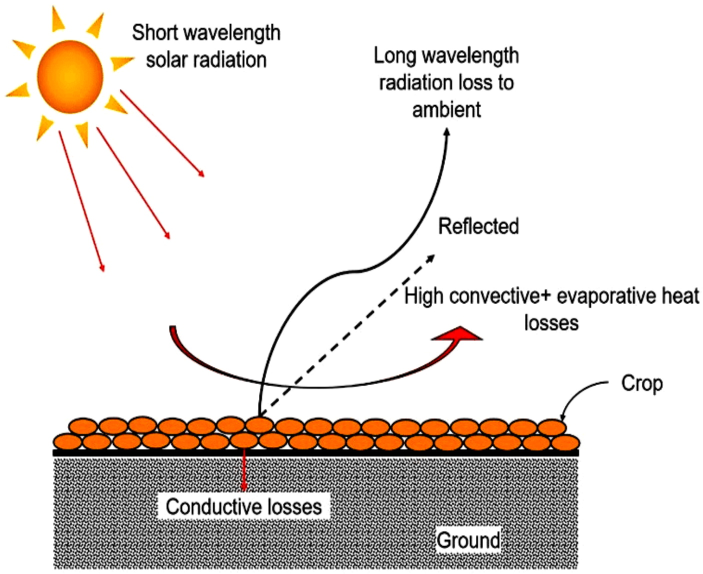


Figure II-2 Open sun drying

II.4 Direct solar dryer

For direct solar dryer **Figure II-3**, the items housed within the cabinet absorb direct solar energy. Natural convection cabinet is another name for this drying cabinet. This type of solar dryer contains product storage chambers that are covered with a clear cover made of glass, plastic, or acrylics. A drying cabinet typically has a shallow and airtight shell that is insulated and allows air to flow into the drying cabinet from the outside [45].

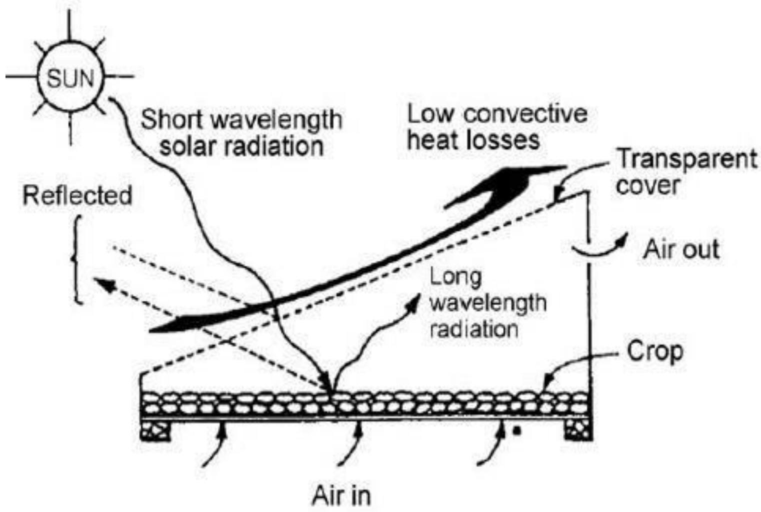


Figure II-3 Direct solar dryer

II.5 Indirect solar dryer

In indirect method of solar drying **Figure II-4,** the sun's radiation energy heats the air passing through the dryer chamber. The presence of hot air in the solar dryer improves the quality of the dried product due to an increase in drying rate. Hot air is sent through the drying chamber. This causes moisture to evaporate and air in the dryer to escape through the drying chamber's ceiling vents. Indirect solar dryers also provide excellent control over drying temperature and pace [46, 47].

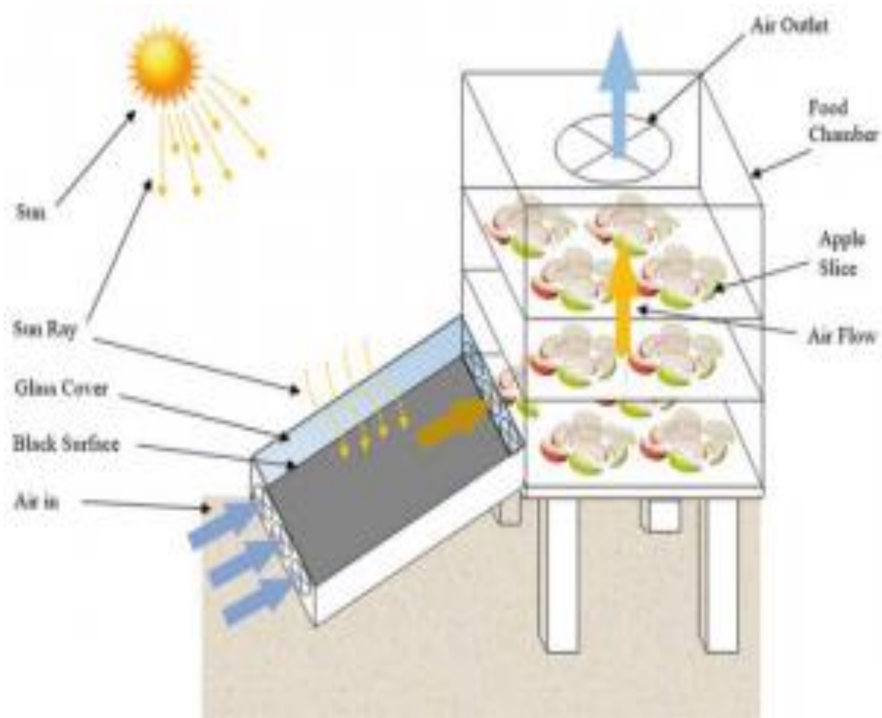


Figure II-4 Indirect solar dryer

El-Sebaii et al. [48] developed a solar dryer under natural convection by employing insulating material like sand which is laid under the absorber. Apples, grapes, onions, and other agricultural goods are dried. According to the findings, using sand as an insulating medium cut drying time by 12 hours. Furthermore, 8 h was greatly decreased since the goods were originally chemically treated for 1 minute in boiling water with 0.40% olive oil and 0.30% NaOH. The authors found that the primary drivers of the drying time decrease were the first chemical treatment and the material utilized for storage. Othieno et al. [49] manufactured solar dryer **Figure II-5** for drying maize. A glazed natural convection solar air drier with a 1 m^2 flat plate collector is used in the dryer the insulated.

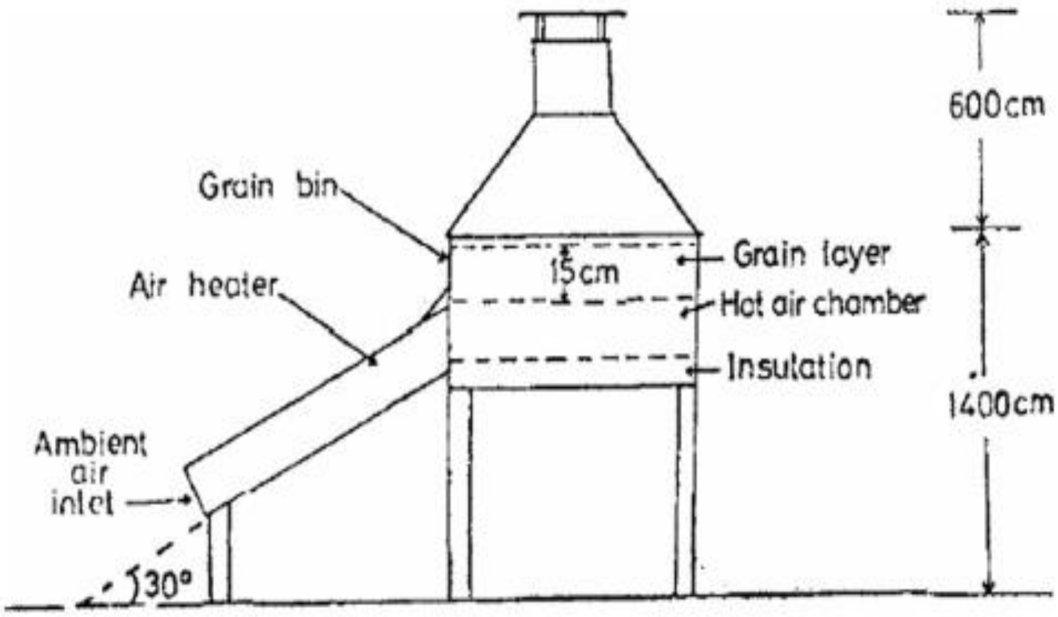


Figure II-5 Orientation natural convection solar dryer with collector slope [49]

drying room is supplied with hot air through a chimney. The dryer is entirely built of hardboard. To improve drying efficiency, the air heater is constructed with a 0.15 m wide air gap to accommodate three layered wire mesh absorbers within the glazed area and a flat plate collector. In three clear days, this sort of drying system may dry up to 90 kg of wet maize with moisture levels ranging from 20% to 12%.

During the examination of the thermal potential of a forced convection type solar dryer running in indirect mode for wood, a layer of pebbles was utilized by Lamrani and Draoui [50] to store heat energy. It was discovered that when the collection area and air speed increased, the drying velocity of wood increased and the drying time for wood decreased. The performance of a forced convection type of solar dryer by heat storage in both sensible heat and phase change material for drying medicinal plants in the western Himalayan area was tested by Bhardwaj et al. [51]. The drier system included a collector with a flat plate for storing iron waste and copper tubes with motor oil for storing sensible heat and paraffin as a phase changing substance, which were kept in two containers and stored at the lowest drying tray. The drying setup was evaluated, and it was discovered that the moisture content was reduced by 9% from 89% to 9% after 120 h. Exergy and energy efficiency were 26.1% and 0.81%, respectively, with sensible and latent heat storage. Sozen et al. [52] designed a solar air heater having tube absorber as presented in **Figure II-6.** A drying cabinet/chamber was built into the system. The use of aluminum wool within tubes enhanced the area of heat transmission. The use of aluminum wool enhanced thermal performance and shortened drying time, according to test results. Because to aluminum wool, the direct power consumption of drying was reduced by 24% 40%.

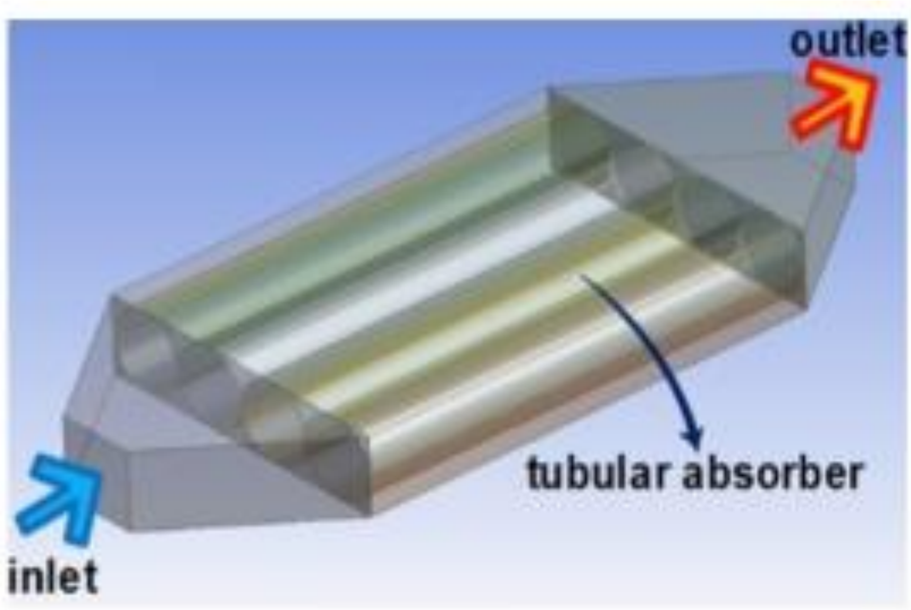


Figure II-6 Solar Heater with Tubular Absorber [52]

Figure II-7 Schematic of Second-pass design of solar air collector [53]

Figure II-7 shows a solar collectors connected to the drying chamber. Neama and Farkas [53] measured the thermal performance of both fins in both horizontal and vertical directions of solar collectors connected to the drying chamber. A copper fins in absorbers are employed in both horizontal and vertical orientations. The experimental results showed that vertical fins boosted dryer efficiency by 10% above horizontal fins. When 2 kg apple slices were dried for 5 hours, the ultimate weights of the slices were 1.16 kg and 1.37 kg in the case of flat and vertical position collectors, respectively. Experimentation was carried out by Masoud et al. [54] on a solar dryer with evacuated tubes in a solar collector coupled to a separate thermal energy storage device. The results of the experiment showed that using thermal energy storage increased thermal energy intake by 1.7% when the mass flow rate of air was 0.025 kg/s and 5.12% when the air flow rate was 0.05 kg/s. It was also discovered that the drying effectiveness of solar drying was 39.9%. Salve and Fulambarkar [55] discovered that employing phase shifting materials stored beneath drying chamber trays increased the performance of an indirect mode solar drier. The flat plate absorber plate was painted black and then coated with activated charcoal. It was discovered that when the flow velocity of air was 8 g/s, the exit temperature from the collector was 96°C. In addition, the collector's efficiency was 33%. **Figure II-8**, Shows a solar drying coupled with photovoltaic panel.

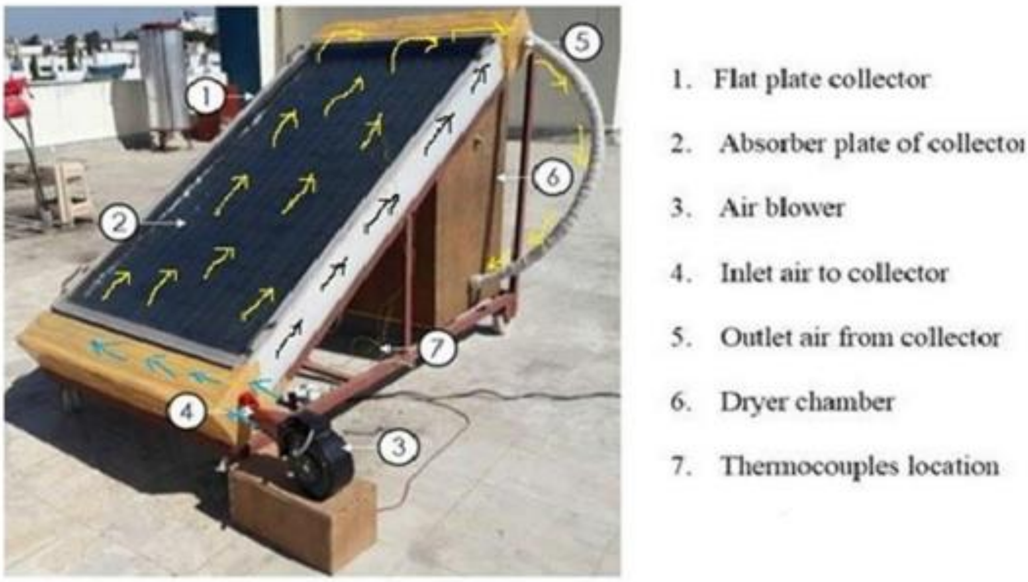


Figure II-8 Indirect Forced Convection Solar Air Dryer [55]

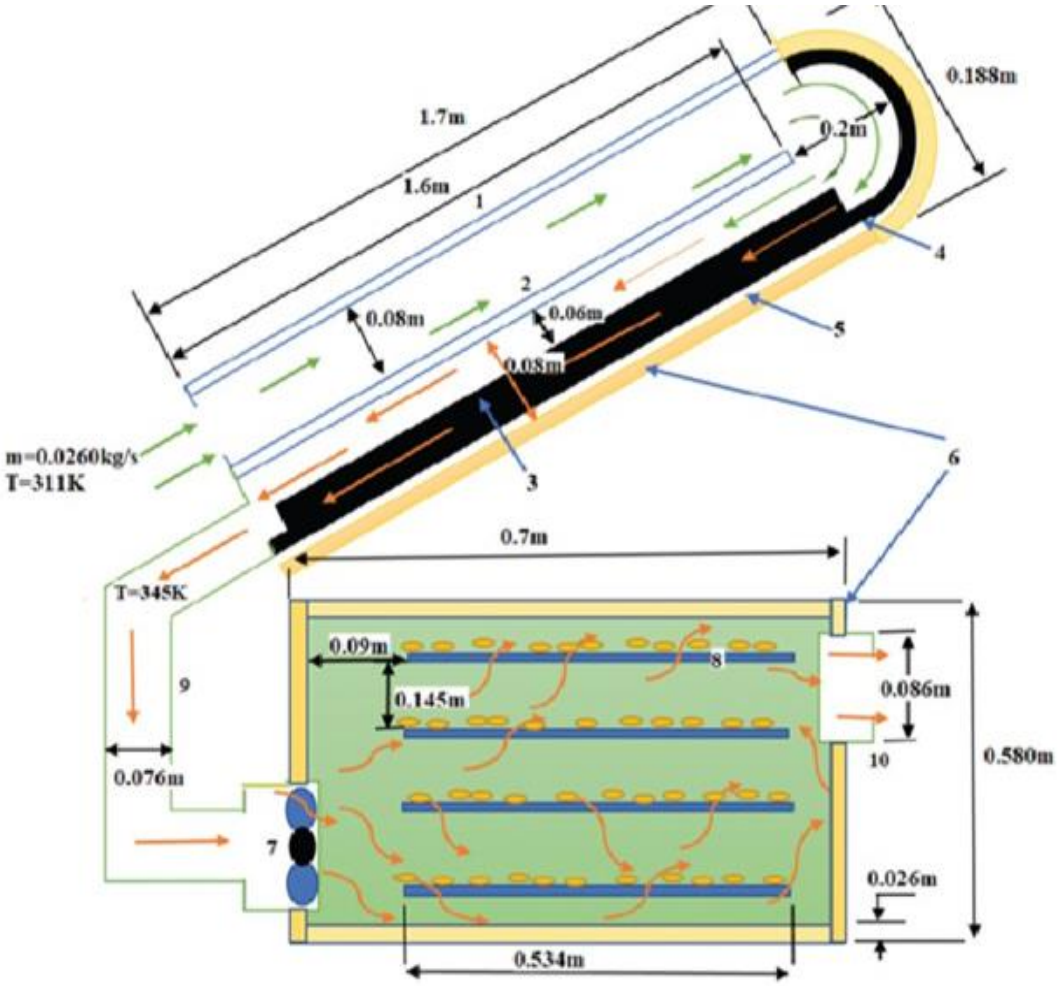


Figure II-9 An Outlay of Developed Banana Solar Dryer [56]

Mutabilwa and Nwaigwe [56] tested the forced convection mode of a solar dryer of the indirect type to dry bananas, as illustrated in **Figure II.9**. The authors compared theoretical and experimental data produced from the CFD simulation. Based on the results of the experiments, it was discovered that using a solar collector with a double pass system resulted in a maximum collector efficiency of 72%. The absorber and fins of the double pass collector were made of aluminum. Khadraoui et al. [57] studied a forced convection indirect type solar dryer with no load and no phase altering material. The maximum temperature present in the dryer trays was increased by 4-16°C in night settings when phase shifting material was used. Kumar et al. [58] used a paraffin-based PCM beneath the absorber plate of a flat plate collector to test the output of a solar drying system. From 10 a.m. to 7 p.m., the quantity of moisture in the mashed potatoes was reduced to 13.30% from 81% when drying potatoes without phase change material and to 8.2% when using a phase change material integrated drier.

Lingayat et al. [59] conducted the experiment utilizing a V-shaped absorber painted in a chosen black, a glass cover, suitable insulation, and an exterior frame, as shown in **Figure II-10.** The V type corrugated absorber has a surface area of 2 m^2 and is built of 0.04 cm thick copper sheet. The rectangular collecting box is built of 0.5 cm thick iron plate. Initially, air was transferred between the absorber gap and the glass to the corrugation of form side 90. Under the absorber, an aluminum sheet provides support for the copper sheet. Insulation is provided by rock wool put between the aluminum sheet and the collector's bottom surface. The weight of the banana was also reduced from 2 kg to 0.56 kg. The average thermal efficiency of the flat plate collector and the dryer efficiency were 31.50% and 22.38%, respectively. Mohan raj and Chandrasekar [60] examined the force convection solar air dryer's efficacy in drying copra as shown in **Figure II-11**. The centrifugal fan, solar air heater, and drying chamber were all components of the solar dryer. Sand was used for sensible heat storage, which was constructed in a 100 mm gap between the heater's insulating layer and absorber plate. The solar heater was placed with a 25^o inclination angle pointing south. In the chamber, three mild steel drying trays were put. Glass wool was used to insulate these pans. After 82 hours of testing, the moisture level of the coconut had dropped from 51.80% to 9.70% in the top and bottom trays, respectively. The thermal efficiency of the dryer was determined to be 24.00%.

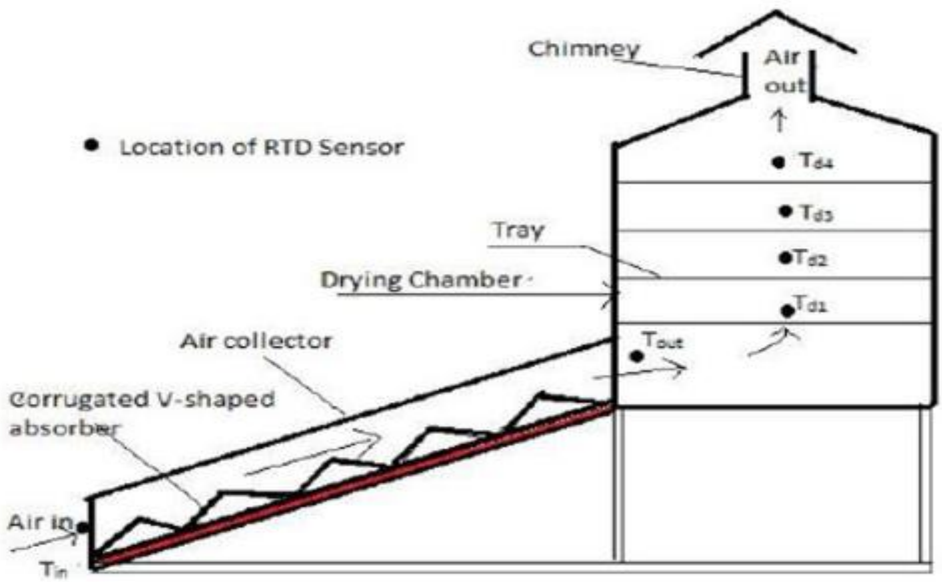


Figure II-10 Schematic of Solar Dryer with Corrugated Absorber [59]

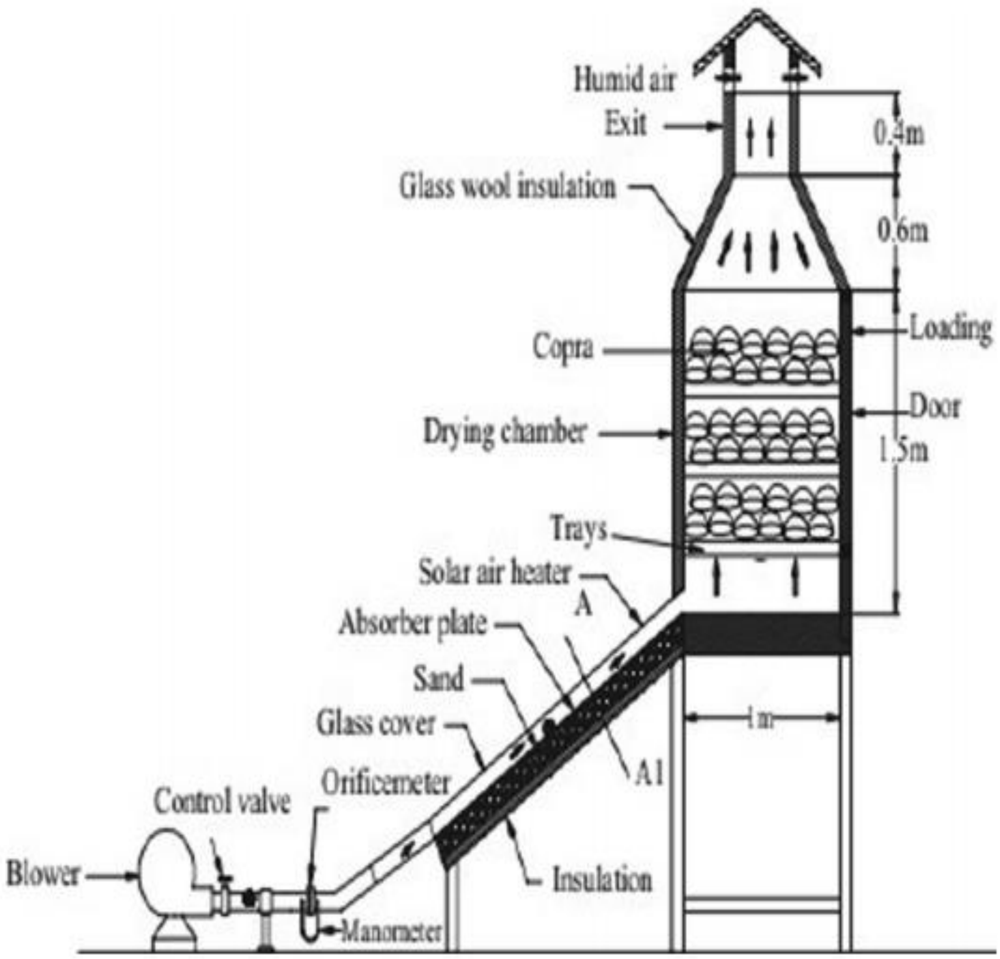


Figure II-11 Schematics of solar air dryer manufactured for drying of copra [60]

Parikh and Agrawal [61] constructed a double-compartment cabinet drier and connected it to a solar air heater to dry potato and green chili chips. As glazing, polycarbonate sheet and glass were employed, while thermos-col was used for insulation. The air temperature climbed from 18°C to 29°C when the glazing was installed. Furthermore, the usage of polycarbonate sheets and glass boosted the drying efficiency to 23.70% when glass glazing was used and 18.5% when polycarbonate sheets were used. Saadeh et al. [62] developed an indirect sun dryer that uses natural by attaching a nozzle to the entrance and reflectors as presented in **Figure II-12**. Mirrors improved the performance of the solar dryer by focusing heat, absorption of heat energy, drying efficiency was high, and a short time interval was required for the drying process. Nozzles enhanced the speed of air, requiring a shorter time period for drying while also improving efficiency. El-Sebaii et al. [48] built an indirect solar dryer with natural convection by employing sand as an insulating material distributed beneath the absorber. Apples, grapes, onions, tomatoes, green peas, and other agricultural goods are dried. According to the findings, using sand as an insulating medium cut drying time by 12 hours. Furthermore, 8 h was greatly decreased since the goods were originally chemically treated for 1 minute in boiling water with 0.40% olive oil and 0.30% NaOH. The author found that the primary causes of the drying time decrease were the first chemical treatment and the material utilized for storage.

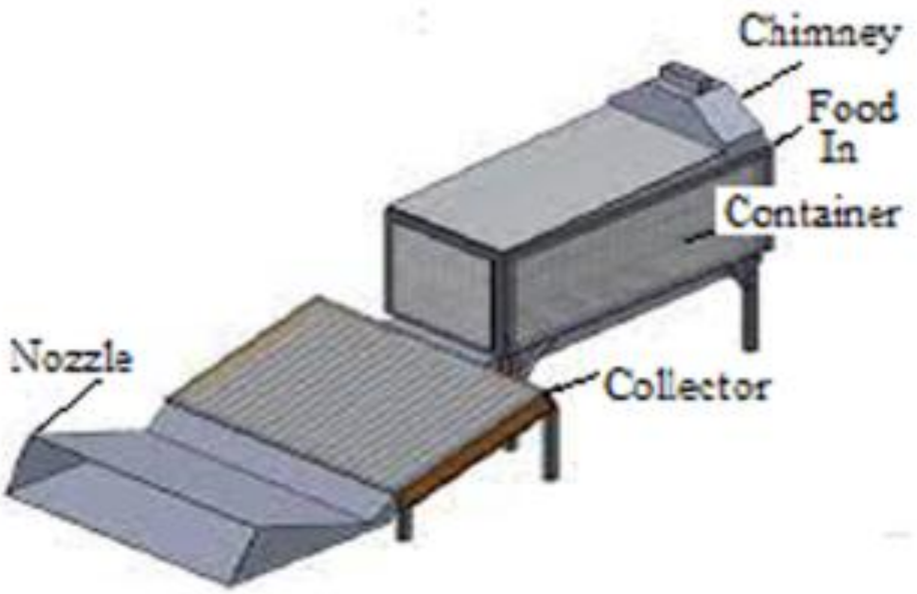


Figure II-12 Schematic of Solar Dryer with Nozzle and Mirrors [62]

To boost performance, Ahmad et al. [63] employed a solar collector with a double pass system and an absorber with fins while creating an indirect forced convection solar dryer. Within 33 hours of the trials/tests, the moisture content of red pepper was reduced to 10% from an initial moisture content of 80%. The design in **Figure II-13** was enhanced by Bhowmik and Amin [64] added reflectors. The experiments revealed that the radiations generated by the absorber inside the collection cannot pass through the glass cover. Reflectors used in the collection focus the heat energy of solar rays in the collecting area, increasing collector efficiency to 61% utilizing reflectors compared to 51% without. The application of collector boosted the overall efficiency of the collector by 10%. Madhan kumar et al. [65] evaluated the effects of an indirect type sun drying system **Figure II-14** consisting of a solar collector and four thin aluminum strips to improve the thermal conductivity of paraffin wax. In both spring and summer, it was discovered that the average picks up efficiency of a sun drying system with fins inserted in paraffin wax is greater than that of a solar drying system without fins inserted in phase change material. The payback period for this sort of solar dryer was estimated to be almost 1.42 years. Sajawal et al. [66] tested a solar air heater using a double pass collector and two distinct phase shifting materials in the absorber plate. The RT44HC, which has a high melting point temperature, was filled with semicircular tubes with fins, whereas the RT18HC, which has a low melting point temperature, was filled with circular tubes. To increase the thermal conductivity of the solar heater, several designs were investigated. It was noted that a configuration including RT44HC on the top side and RT18HC on the bottom side of a double pass collector of a solar air heater provided the maximum efficiency. The overall efficiency rate was 71.9%.

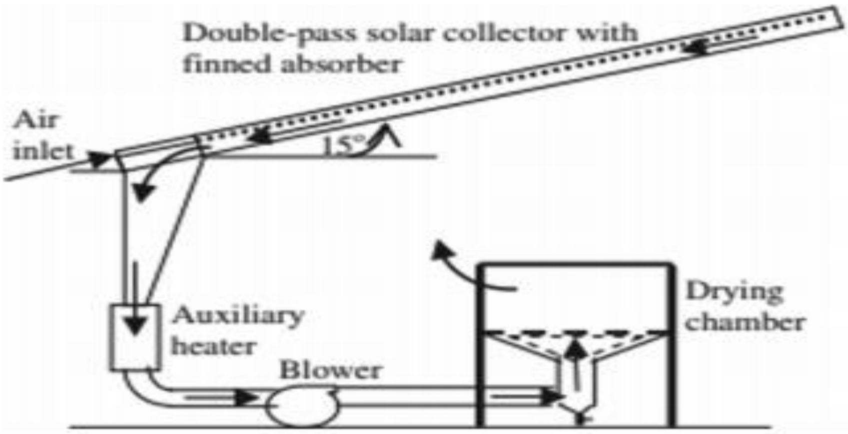


Figure II-13 Schematic View of the Flat Plate with Reflector [64]

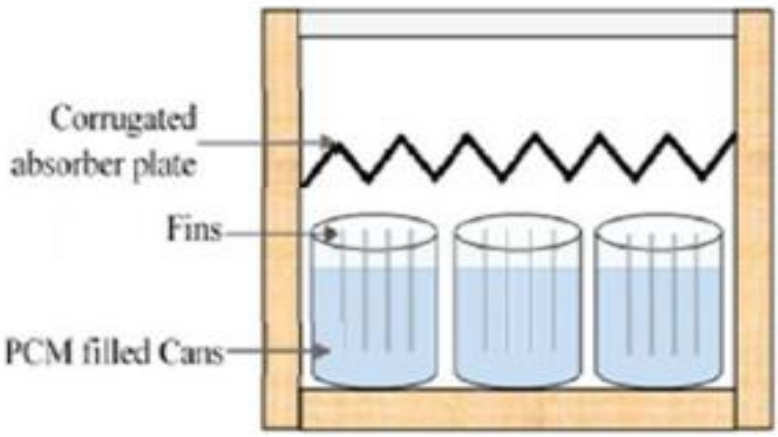


Figure II-14 Schematic of solar collector with Phase Change Material with fins [65]

II.6 Mixed solar dryer

A solar hybrid dryer is a device that combines the benefits of both direct and indirect sun drying methods. Direct sunlight exposure causes drying of a product in this sort of drier, as does hot air from the collector. The temperature of the air is first raised in the solar collector system before being transported to the drying cabinet. The product dries out during this phase owing to moisture loss through convection. To expose items to sun rays, transparent material is partially or entirely covered on the drying chamber [45].

II.7 Machine learning algorithms

Many engineering challenges make use of machine learning, both for regression and classification. Its basic concept is to do learning on a set of data and then create predictions depending on the data and learning type. In the prediction of drying characteristics such as moisture content and moisture ratio, two separate machine learning methods - ANN and SVM - are applied. The drying time, moisture in the drying chamber, concentrated solar radiation, nonconcentrated solar radiation, and greenhouse temperature are all included in the dataset. The information is then separated into two pieces. The first component is used in algorithm training and comprises 70% of all datasets, while the second part is used in algorithm testing and includes the remaining 30% of all datasets. In the shuffled sample mode, the data is divided. The grid search approach is used to tweak the parameters of the algorithms. The subsections below provide an overview of the algorithms utilized in this article [67].

II.8 Conclusion

The efficient utilization of solar energy, which is a free, eco-friendly, and stable source of energy, is the future of green energy. This research examines the ways for improving the performance of solar drying systems. Because of its high thermal energy storage capacity, phase transition materials have received a lot of attention in recent research. Both thermal energy storage systems and forced convection are required to dry agro-food or medicinal items at night while maintaining dependability and control. Photovoltaic panels serve as a source of electrical energy, supplying it to various components such as a blower or heat pump. The effectiveness of a solar dryer is determined by a variety of factors such as solar energy insolation, surrounding temperature, air velocity, air humidity, product type, starting moisture existing in the product, weight of the product to be dried, and so on. More study is suggested to examine the uniform velocity and temperature of the air inside the drying chamber.

Realization of Different Indirect Solar Dryer models for performance’s enhancement

III.1 Introduction

Modern world is seeing the cycle of technological transition and creativity to boost living standards., such as deterioration of agricultural products to which worry farmers and consumers [72]. It is estimated that post-harvest losses of agricultural products occur worldwide between 10 and 40%. Such losses are higher in developing countries [73]. To reduce these losses, we have to use different techniques such as solar drying, in which it is an effective method for food preservation, inhibits bacteria and yeasts via water removing. Solar drying used from the past for preserving industrial and agricultural products [74]. In recent years, through this technique the agricultural products losses have been reduced [75]. Many studies considered that solar drying processes as an alternative to traditional open-air drying and/or modern fossil-fuel or electric drying systems. Many types of solar drying exist, such as solar dryer drying and natural solar drying. The last type is very slow, it cannot prevent the continued control of the drying process, also the control of the final moisture is very difficult [76]. In general manner, solar dryers are classified, following their working mode, into two major classes: natural convection solar dryers, also called passive dryers and forced convection solar dryers [77].

During the last decade, solar dryers has been used with success for drying agricultural products. Many scientific researches have been carried out experimental, theoretical and simulation studies for improving solar dryer system efficiency. A solar dryer system is provided by Yuan et al. [78] for carpet drying at large-scale industry. A flat plate solar air heater has been installed for improving its efficiency. The collector's model thermal efficiency has been checked according to international standards.

Ndukwu et al. [79] performed an exergy-energetic study of solar dryer assisted by wind generator power fan source. In addition, glycerol used as heat storage in this system. They found that the integration of wind generator with thermal storage effected positively on energy efficiency. in which, the drying time and energy consumption increased considerably. Murali et al. [80] assessed the design and performance of solar hybrid dryers for shrimps drying. They used water as a thermal energy storage medium of sensible heat energy for drying process during sunshine hours. The authors reported the maximum temperature of outlet water from solar collector of 73.5 °C at 01:30 pm. In addition, the drying and maximum collector efficiency obtained were 37.09% and 42.37%, respectively.

Comparative assessment of solar and heat pump dryers with regards to exergy and exergoeconomic performance has been investigated by Atalay [81]. The author handled each components of the systems performances alone and found that the fan is the main component in improving the performance of the solar dryer. In addition, it was shown that the condenser is a very effective component for the performance of the heat pump dryer. Khanlari et al. [82] studied the performance enhancement of a greenhouse dryer using the analysis of a cost-effective alternative solar air heater. Both computational fluid dynamic (CFD) and experimental investigation of tube-type assisted greenhouse dryer have been carried out. The authors found that the mean of thermal effectiveness of simple tube-type heater reached 56.8%. Furthermore, they obtained that the integration of greenhouse dryer leads to reducing drying time until 30%.

Solar fuel energy was exploited by Moghaddam et al. [83] for drying lemon verbena in a continuous flow dryer. They found that in compined mode i.e. solar with gas, the fuel consumption at temperatures of 30 and 40 °C was zero. The optimal operating conditions namely drying air speed and temperature for this dryer were 2 m/s and 39.54 °C, respectively. Different agriculture product such as peanut, potatoes, tomatoes and medicinal plant have been dried using solar dryer in southeast Algeria. Meanwhile, always the problem is the limited loading capacity that didn't exceed 2 kg of dried product [84-87].

The present chapter aims to represent the realization of three different models of indirect solar dryer, which are (1) indirect Solar dryer with the integration of local and waste materials for heat storage, (2) indirect Solar dryer assisted by Parabolic-trough solar concentrating systems and (3) indirect Solar dryer assisted by parabolic solar dish concentrator.

III.2 Realization of different Indirect Solar dryer models for performances enhancement

III.2.1 Improvement of passive Indirect Solar Dryer using storage materials

Despite the fact that a set of thermal storage materials have been tested in different design, scientists have continuously looked for cheap and efficient alternative with improved design for one environment to another. Materials like, waste iron sheet is discarded after completing turning and milling process. The specific heat capacity is about 0.46 J/g °C. Therefore, an important valuable source of thermal storage in low-temperature solar system design.

Indirect passive Solar Dryer integrated with storage materials under natural convection mode has been fabricated for studding the dyring performance of menthe. The fabricated experimental set up comprises of a solar energy gatherer (80cm×60cm×15cm) and drying unit (40cm×40cm×50cm) as shown in **Figure III-1**.

Figure III-1 montrant notre séchoir solaire

In order to test the effect of storage materials, three passive solar dryers which contains three different collectors (collector occupied with steel chip, collector occupied by Biskra flint stone and collector supported by an iron sheet) of the same dimensions and sizes. The added materials act as energy storing material for storing heat during sunshine time and maintaining uniform air (for drying) temperature which flows within drying unit. The dryers contain a circular nozzle from below or exits a tube with a diameter of 60 mm from above, going to the drying chambers, where the drying chambers are of the same dimensions and sizes.

Figure III-2 The collectors

The drying chambers is a wooden box with a length of 40cm, a width of 40cm and a height of 50 cm, and it contains a circular nozzle from the bottom up to 60mm and a nozzle in top of the box to also extract hot air 60 mm and contains a shelf instead to place the product to be dried there as shown in the following **Figure III-4**.

Figure III-3 Drying chambre.

The collector receives the sun's rays, as the incoming air mixes through the lower openings of the collector absorbs the heat, then the hot air inside the receiver moves upwards to the drying chamber. Hot air enters through the bottom opening of the chamber. It moves upwards where it passes over the shelf where the product to be dried is placed. After that, hot air comes out of the upper chamber nozzle.

Figure III-4 Showing how to put mint in à drying chamber.

III.2.2 Improvement of Indirect Solar Dryer using Parabolic-trough solar concentrating systems

Parabolic trough solar collector is one kind of the interesting concentrating collectors, being extensively utilized in the field of desalination, electricity production, heating of space, and so on. Conventional receiver used in Parabolic trough solar collector is the vacuum tube. But its cost is very high, and its life cycle is short. Therefore, many researches focus on investigation of new solution such as cavity absorbers.

In this work, parabolic trough concentrating system with arc type metal cavity absorber was used for providing heat for banana drying system. In order to increase the absorbed energy, the cavity absorber was filled with a set of metal fins. This action will be ensuring that stable heat energy provided by the PTC system is enough for banana drying process.

Diagram of parabolic trough concentrating solar heating for banana drying system was represented in **Figure III-6**. The solar dryer coupled by cylindro-parabolic concentrator is composed of two essential parts, a cylindro-parabolic solar reflector and the absorber tube.

Figure III-5 Solar dryers with cylindrical-parabolic collector

The PTC for banana drying process was depicted as follows. Firstly, when sunlight arrived at the parabolic trough concentrator mirror, the manual tracker was adjusted to make the absorber cavity match with focal length of the PTC in order to reduce sunlight losses. Secondly, the blower was functioned and the air flow absorbed the heat energy from the cavity surface. When temperature of the hot air reached needed temperature in the drying room, the pretreated banana pieces was put into the drying room for drying operation. Next step, when finishing the drying process, dried banana was separated from the airflow.

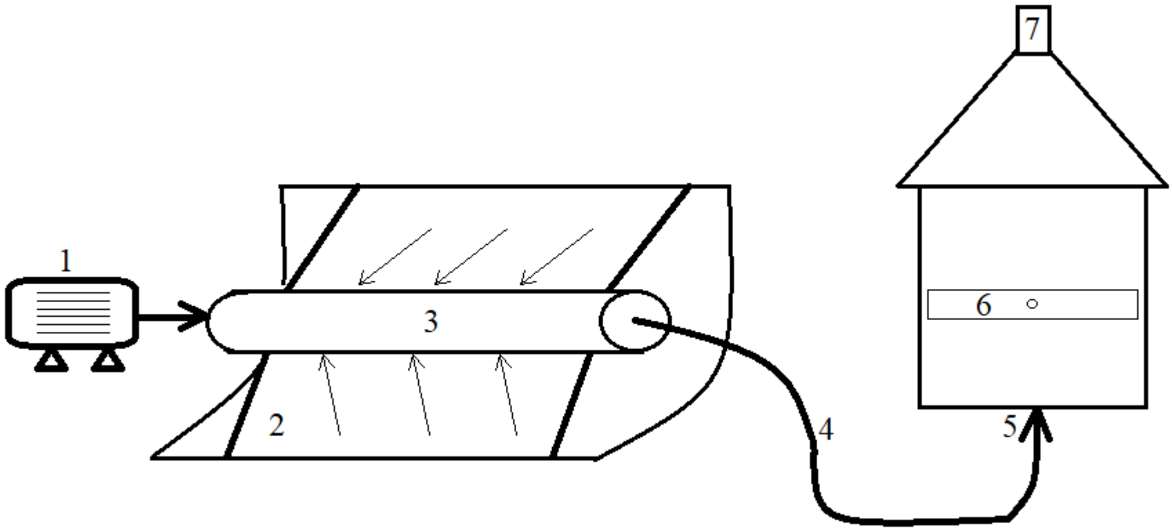


Figure III-6 descriptive diagram of Solar dryers with cylindrical-parabolic collector.

1- A centrifugal blower of 100 W of power consumption with mass flow rate of 1.65 m^3/min
2- Parabolic-trough solar concentrating systems
3- Absorber cavity
4- A pipe for hot air flow
5- Drying chamber
6- Dried Crops
7- Moisture air exhaust

III.2.2.1 Essential part of Indirect Solar Dryer using PTC

- **Parabolic-trough solar concentrating systems**

The cylindrical-parabolic reflector is a type of solar thermal energy collector, the technical-economic performance is the fact of successfully producing the very good quality mirror panels with a reflector of 94%.

Figure III-7 Cylindrical-parabolic reflector

- **Absorber cavity**

The cylindrical-parabolic concentrator receiver in prismatic form over the entire length of the reflector, The receiver metal must have good conductivity, we have chosen iron (whose thermal conductivity is around 80 W/ k.m^2) , the receiver absorbs the radiation concentrates on a black surface and converts the heat generated to the drying air, the receiver contain interior has barriers to let the air stay longer for the well heated.

Figure III-8 Absorber cavity

III.2.3 Realization of Indirect Solar Dryer using parabolic solar dish concentrator

The goal of the present work is to test a new design of solar dryer, which is assisted by parabolic solar dish concentrator for improving its performances; the role of parabolic solar dish concentrator is to get high temperature in the drying chamber without using external source such as electrical resistance or heater gas. The experiments were carried out during the wind period when the weather was volatile. This situation limited the opportunity of natural drying so that forced dryers are often the main solution for drying agro-food products.

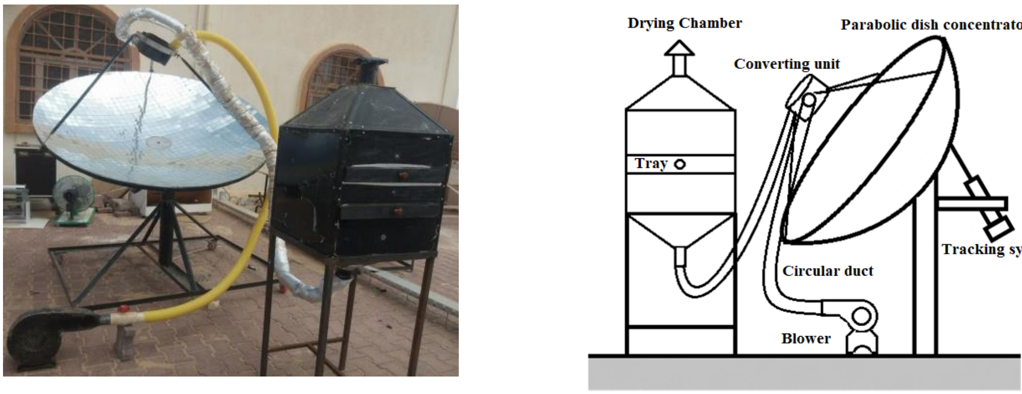


Figure III-9 Solar dryer with dish collector

The experimental set up of the solar dryer has been located near Mechanical Engineering Laboratory, El Oued University, Algeria at a longitude 6.8674° East and latitude 33.3683° North. The experiments were carried out during April 2018.

The graphic and image views of the realized dryer are shown in **Figure III-9**. The set up mainly contains the following: (i) parabolic dish concentrator (ii) converting unit (iii) drying chamber, (iv) tracking system and (v) blower. The parabolic dish is oriented to the satellite receiver and it is used as a solar radiation receiver, it has 1.8 m of diameter ; the distance between the focal point and dish is 0.84 m, it is fitted with mirrors with a small surface of 0.0025 m^2. The converting unit placed at foyer point of the parabolic dish concentrator **Figure III-10** is a steel cylinder with thermal conductivity of 50.2 W m^{-1} K^{-1}, diameter of 0.17 m and length of 0.15 m. It is closed with two plates, one of which has fins to increase the heat exchange surface, it has two holes, the first to enter the cold air and the second to exit the hot air. Tracking system **Figure III-11** is a semi- automatic system consists of one jack for moving the parabolic dish vertically, horizontal moving of the parabolic dish done manually.

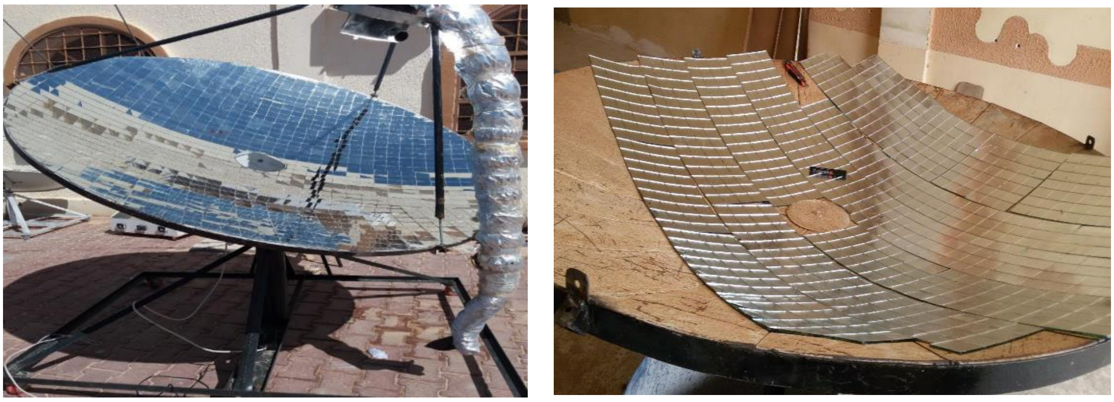


Figure III-10 Parabolic dish Concentrator

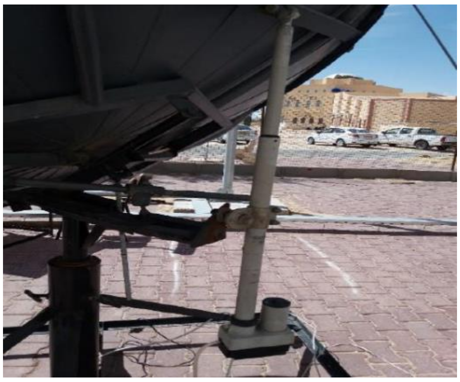


Figure III-11 Tracking system

Results and Discussion: Experimentation of Different Indirect Solar Dryer

IV.1 Test and evaluation of Indirect Solar Dryer using parabolic solar dish concentrator

From previous chapter, it is found that the indirect solar dryer using parabolic solar dish concentrator model enhances the overall performance of the system. In addition, this model characterizes by reducing operation time and the possibility for increasing the drying volume. Furthermore, this model distinguishes by its simple realization and its low cost. Therefore, the following results is based on experimentation and assessment and moisture removal (drying) kinetics of indirect solar dryer using parabolic solar dish concentrator of chili slices and Groundnut.

IV.1.1 Chili drying using Indirect Solar Dryer using parabolic solar dish concentrator

This work aims to enhance two criteria for the realized solar dryer which are the air temperature and drying time. The experiments showed that the temperature reached to 510 °C at noon in the focus point at the parabolic solar dish concentrator. The drying time was decreased considerably and it was 5 hours for red chilli. The temperature in the drying chamber was 55 °C. These operating conditions depicted that this solar dryer assisted by parabolic dish concentrator is very useful for agricultural drying and it can be tested at macroscale industry drying.

Figure IV-1 Converting unit

Ambient air enters into the converting unit Erreur ! Source du renvoi introuvable.**Figure IV-1** through a circular duct, in which its temperature is increased. For maximizing the exploitation of the incident solar radiation on the converting unit, tracking system is used and is controlled by light dependent resistor. The solar drying chamber is fabricated by wood. It consists of two wooden enclosures containing glass wool for thermal insulation, and it has two openings, one of which at the bottom to enter the hot air in and the other one at the top to evacuate the humid air, it has several placements for trays installation on which to dry red chili is positioned, the dimension of each tray is 0.40 m × 0.40 m. The dryer duct has divergent section welded with drying chamber for uniform distribution of the air going out. The drying chamber dimensions are 0.5 m×0.5 m×0.5 m.

The realized dryer can be considered as an indirect one because the hot air enters only from the converting unit via blower for accelerating drying process. A centrifugal blower of 100 W of power consumption with mass flow rate of 1.65m3/min is connected between converting unit and drying chamber. A gate valve controls the mass flow rate has been used. During the drying process, the mass flow rate of the drying air was maintained at the maximum blower capacity. The drying experiments has been performed in April 2018 during the wind period when the open sun drying ie natural drying is very hard due to the dust.

The red chili peppers were collected from a local farm (El Oued region, southeast of Algeria) and washed with water. To examine the drying behavior, 250 g of red chili were distributed uniformly in one tray. The drying experiments of red chilies slices were performed on April 24, 2018 from 9:00 am and kept until 3:00 pm.

(a)

(b)

Figure IV-2 Snapshot of red chili (a) before and (b) after drying in solar dryer assisted by parabolic dish concentrator

During the drying operations, incident solar radiation on the parabolic dish concentrator was tracked hourly using a pyranometer (model: PYR-1307 solar power meter, accuracy ± 1 W/m2), placed near the solar dryer on a clear, unshaded field. K-type thermocouples (model BTM-4208SD, accuracy of±0.1 °C) were positioned at various locations of the drying system namely converting unit, inlet and outlet of drying chamber, and in outer of drying system for ambient temperature. The air-drying temperature in the realized dryer was chosen in order to kept the temperature inside the drying chamber ranging between 40 °C and 65 °C. Outputs from pyranometer and K-type thermocouples were connected with a data acquisition system (BTM-4208SD) for nonstop monitoring. A digital weighing balance (CP214, OHAUS, accuracy of ± 0.1 mg) was placed near the drying chamber. It is used for determining the weight of red chilli peppers sample each 10 mn.

Initially, the moisture content obtained through consecutive weightings of red chili sample during the experimental tracks, is defined as the wet basis and converted to dry (g water / g dry matter), The moisture ratio (MR) was expressed as:

$$MR = \frac{M - M_e}{M_i - M_e} \qquad (1)$$

where M is the moisture content at given time t, Me is the moisture content of equilibrium and Mi is the initial moisture content.

The air velocity and moisture content of samples in in the drying chamber were measured using a humidity/anemometer tester (AM-4205A Model, accuracy: 1% RH and ±0.2 m/s).

The solar radiation and the temperature in converting unit during the drying process were acquired and presented in **Figure IV-3** Red chili was dried during 5 h in one day; consequently, a middling of solar radiation intensity is booked and designed. The solar radiation ranged from 300 W/m2 to 580 W/m2 during drying process with average of 440 W/m2. The minimum solar radiation was detected at 3:00 pm and the culmination at 11:45 throughout the drying process.

It seems obviously that the temperature into converting unit augmented with solar radiation intensity, in which it was reached to 510 °C.

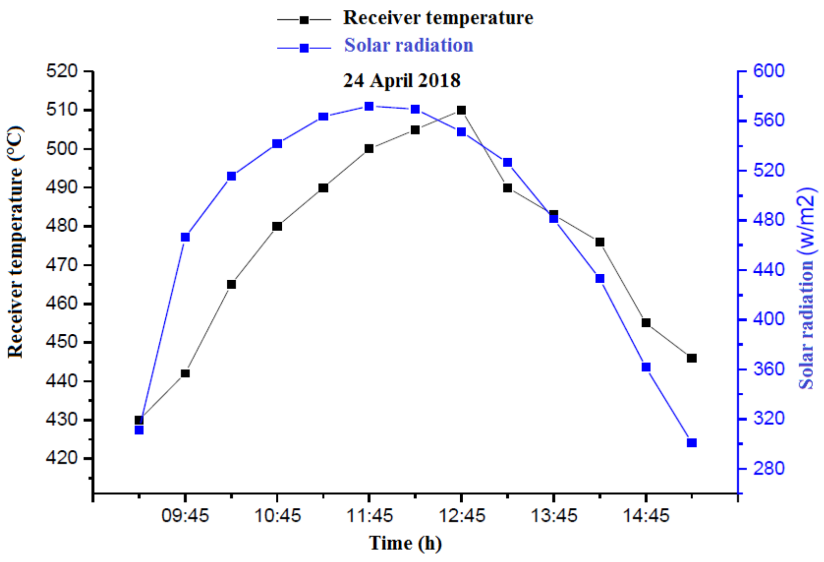


Figure IV-3 Converting unit vs. Solar radiation during the drying experiments

The variation of ambient temperatures and the temperatures at converting unit were monitored and plotted in **Figure IV-4.** It looks evidently that the temperature inside the drying chamber augmented between 15 and 25 °C overhead the ambient temperature during red chili drying process. At the same period, the moisture content in the dryer red chili decreased by 90% within 5 hours **Figure IV-5**. Similar remarks were made during chili drying in [17, 18].

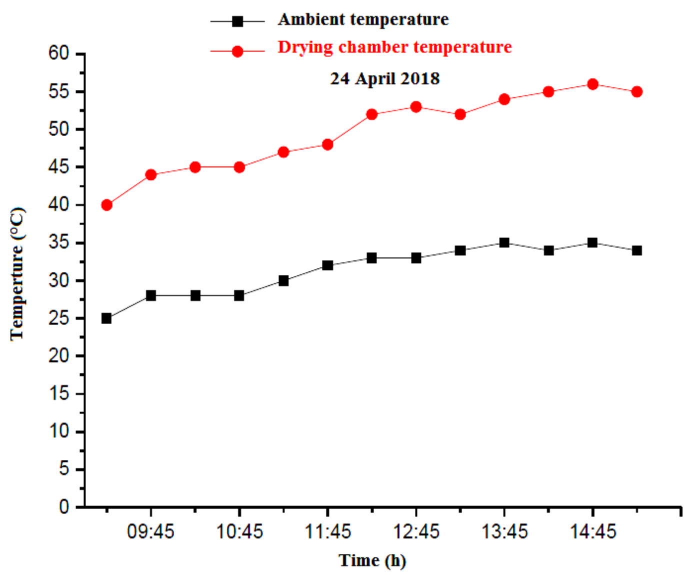


Figure IV-4 Ambient Temperature vs. drying air temperature during the drying tests

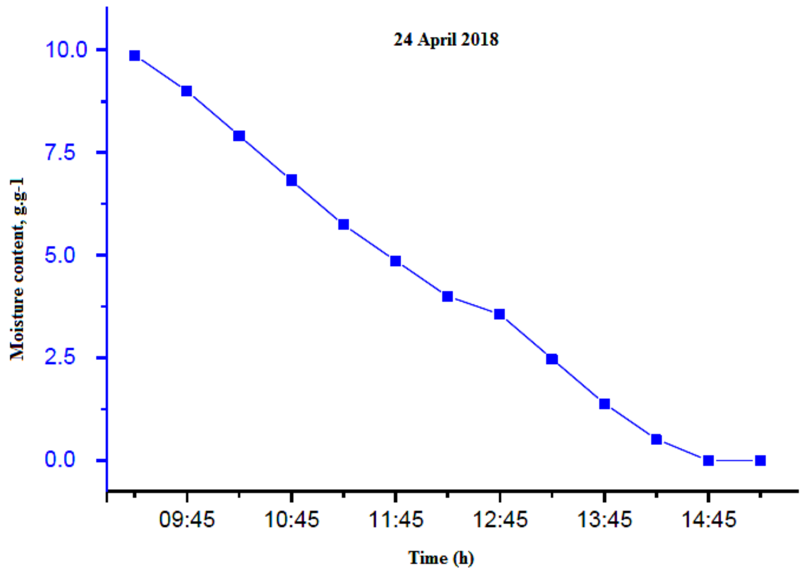


Figure IV-5 Change in the red chili moisture content vs. drying time.

Based on the experimental results, the proposed mathematical model, constants and coefficients were evaluated in terms of the drying air temperature as follows:

$$MR = A_0 + A_1 t + A_2 t^2 + A_3 t^3 \quad (2)$$

Where

$$A_0 = 0.971$$

$$A_1 = 7.667$$

$$A_2 = 27.91 \quad (3)$$

$$A_3 = 21.316$$

$$r = 0.997$$

The above model can be utilized to evaluate the moisture ratio of red chili pepper at any time within the drying process. The accuracy of the proposed model was tested by comparing the computed moisture ratio under any time with the detected moisture ratio during the drying experiments. The performance of the proposed model at the adopted drying air temperatures is depicted in **Figure IV-6**.

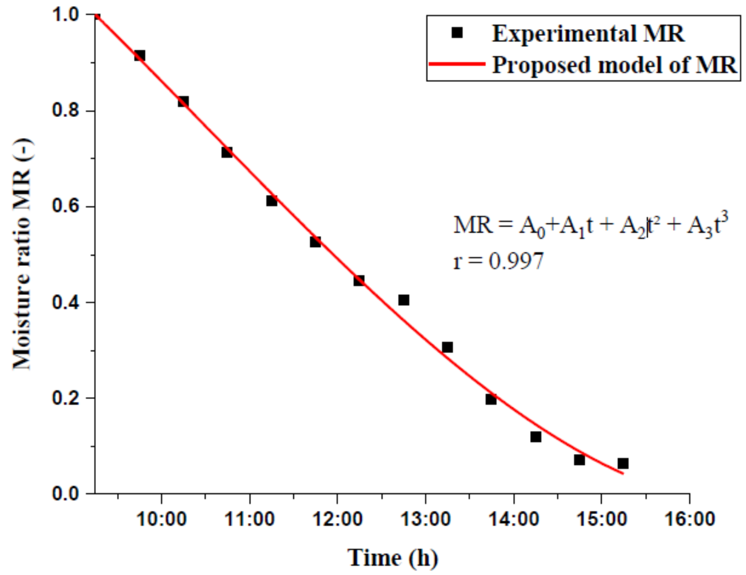


Figure IV-6 Proposed mathematical model for red chili pepper under El Oued climate region

An indirect type solar dryer assisted by parabolic dish concentrator was realized. This solar dryer was tested during the wind period under arid zone climate condition at laboratory, southeast of Algeria. The following findings were concluded based on the red chili drying experiments:

- The mean solar radiation intensity throughout drying process of red chili was detected around 440 W/m2.

- The medium ambient temperature and drying temperatures at tray during the drying experiments were 30 °C and 50 °C, respectively.
- The moisture content in the dryer red chili decreased by 90% within 5 hours.
- The conditions inside the dryer (temperature and moisture content) were ideal for drying red chili. In most solar dryers, drying the samples down to a safe moisture content about 10% water basis (w.b) takes more than a day. Meanwhile, 5 hours were enough for drying red chili using the parabolic dish concentrator solar dryer.
- According to the obtained results, the integrated drying unit can contribute considerably to realize efficient macro scale solar dryer in the future.
- However, it is noted that the parabolic dish concentrator solar dryer needs further research on the influence of all affecting parameters for practical industrial applications of agriculture products.

IV.1.2 Groundnut drying using Indirect Solar Dryer using parabolic solar dish concentrator (ISDPSDC)

IV.1.2.1 Groundnut drying characteristics

Groundnut samples are selected before drying, four samples of close weight 280 g are taken for drying using four techniques, the first in the open air, the second in the dryer assisted by turning chip in the receiver, the third assisted by rocks in the receiver, and the fourth assisted by fins in the receiver. The experimental curves below show the drying properties of groundnut in terms of moisture content as a function of time, well the experimental curves of the drying rate with moisture content.

By observing the conventional drying curve, two drying periods can be distinguished. The first in which the water content decreases rapidly, and the second where this decrease becomes slower until the end of drying. The water content was determined at regular intervals during the drying times.

IV.1.2.1.1 Determination of water content in peanuts by oven drying

- **Objective of the test :**

The water content test is a method used to determine the quantity of water present in a groundnut. This test provides valuable information about the moisture content within the groundnut, which is crucial for various purposes such as storage, processing, quality assessment, and drying. By accurately measuring the amount of water in the groundnut, this test helps in determining its overall moisture status, enabling better decision-making regarding its usage and handling.

$$X = \frac{\mathrm{Mw}}{\mathrm{Ms}} \times 100\ (\%)$$

Mw: Mass of water in groundnut (sample)

Ms : Mass of peanut solid particles (sample)

The water content is expressed as a percentage.

Figure IV-7 Freshly harvested peanuts

b.Equipment :

- Peanut (sample)
- Containers
- Oven with temperature control (drying oven)
- Balance

c.Procedure :

- Weigh the mum container of the lid (M1). Identify it with a label.
- Place the sample in its natural state in the beaker and weigh the whole (sample + beaker), (M2). Preferably keep it closed in order to keep the humidity of the sample.
- Place the assembly (sample + beaker) in the oven with temperature set at (103 ± 2)°C once the beaker is in the oven, do not forget to remove the lid.
- After 24 hours remove the beaker with the dry soil. Replace the lid and weight (M3) using the same scale.
- Determine the water content W expressed as a percentage :

$$W = \frac{M_2 - M_3}{M_3 - M_1} \times 100$$

M1= Mass of the beaker.

M2= mass of beaker + mass of wet peanut.

M3= Mass of the beaker + Mass of the dry peanut.

Figure IV-8 Laboratory beaker

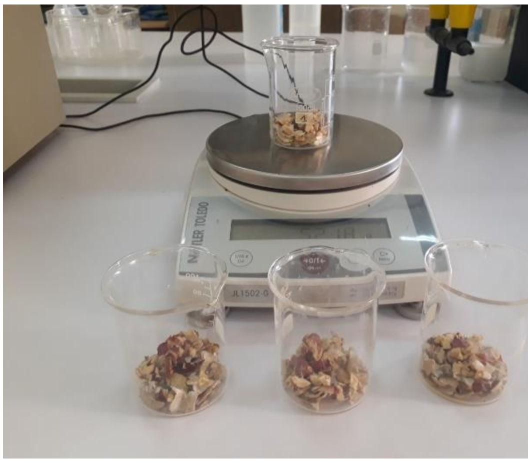


Figure IV-9 Weight of peanuts before and after delivery drying oven

d.Desiccator :

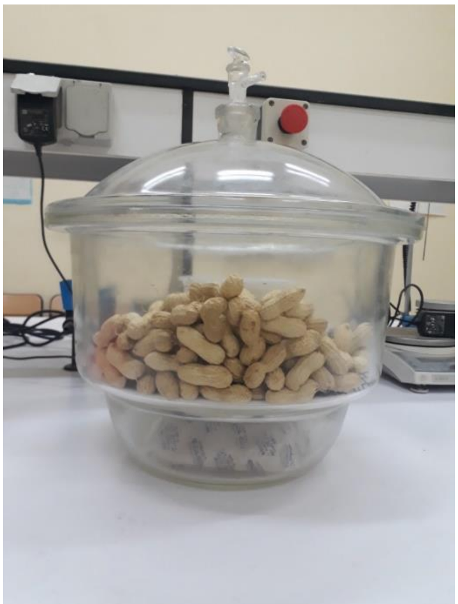


Figure IV-10 Desiccator

A traditional desiccator consists of a glass bowl and a lid, both equipped with thick glass rims that can create an airtight seal when lubricated. Below the perforated ceramic disk, a hygroscopic chemical, known as desiccant, is placed. This desiccant absorbs water from the surrounding air. On top of the disk, a sample in a beaker or crucible is positioned. The main purpose of the desiccator is to either remove moisture from a chemical substance or prevent it from absorbing moisture from the atmosphere

IV.1.2.2 Mathematical models of solar drying in thin layers

The problem of modeling solar drying curves generally consists in developing a function satisfying the following equation: $MR = (t)$.

$$MR = \frac{Mt \ - Me}{M0 \ - Me} \tag{1}$$

With M_t, M_e and M_0 are the values of the water content (dry basis) respectively at time t, at infinity (equilibrium) and at t=0. Drying rates were calculated using the following equation:

$$\frac{\mathrm{dM}}{\mathrm{dt}} = \frac{M_{t+\Delta_t} - M_t}{\Delta t} \tag{2}$$

With M_t+Δt and Mt are the water content at time t and the water content at time t+Δt in kg water/kg dry matter, respectively, t is the drying time in minute. Given the complexity of the phenomena occurring during the drying of a product, several authors have proposed mathematical models in the form of empirical or semi-empirical relationships to describe the drying curves. The equations of these models express the evolution of the reduced water content MR as a function of time. These formulas contain constants which are adjusted to reconcile the theoretical results with the experimental drying curves.

Therefore, they are valid only in the field of experimental investigation for which they were established. **Table IV. 1** groups together a few empirical models reported in the literature to describe the kinetics of solar drying in thin layers of a product.

Table IV. 1 Mathematical models of solar drying in thin layers

N°	Models	Equations	References
1	*Newton (Lewis, Exponential, Single exponential) Model*	$MR = exp(-kt)$	*[Lewis, 1921]*
2	*Page Model*	$MR = exp(-kx^n)$	*[Xanthopoulos, et al. ,2007]*
3	*HerdersonandPabis (Single term, Generalized exponential) Model*	$MR = A\,exp(-kt)$	*[Zhang, et al. ,1991]*
4	*Modied Page Model*	$MR = exp(-(kx)^n)$	*[Midilli, et al. ,2002]*
5	*Logarithmic Model*	$MR = A\,exp(-kt) + c$	*[Yaldiz, et al. ,2002]*
6	*Midilli-Kucuk (Midilli, Midilli et al.) Model*	$MR = A\,exp(-kt^n) + bt$	*[Midilli, et al. ,2002]*
7	*DiffusionApproximation (Diffusion Approach) Model*	$MR = A\,exp(-kt) + (1-A)\,exp(-kbt)$	*[Balbay, et al. ,2012]*
8	*Verma et al. (Modified Two-Term Exponential) Model*	$MR = A\,exp(-k1t) + (1-A)\,exp(-k2t)$	*[Ruiz, et al. ,2013]*
9	*Two-Terms Model*	$MR = A\,exp(-k1t) + b\,exp(-k2t)$	*[Akpinar, et al. ,2004]*
10	*Two-TermsExponential Model*	$MR = A\,exp(-kt) + (1-A)\,exp(-kAt)$	*[Corzo, et al. ,2011]*

The most appropriate model will have to be identified among these ten different models proposed by the authors as indicated in **Table IV. 1**. Regression analyzes were carried out using the "Origin Pro 9.0" software.

The coefficient (R^2) was one of the main criteria to select the best model to define the drying curves. In addition to (R^2) the various statistical parameters such as reduced khi-square (x^2) and root mean square error (RMSE) were used to determine the goodness of fit. These coefficients can be calculated as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pré,i}\right)^2}{\sum_{i=1}^{N}\left(\overline{MR_{exp}} - MR_{exp,i}\right)^2} \quad (3)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pré,i}\right)^2}{N-n} \quad (4)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pré,i} - MR_{exp,i}\right)^2} \quad (5)$$

Avec (6)

$$\overline{MR_{exp}} = \frac{\sum_{i=1}^{N} MR_{exp,i}}{N}$$

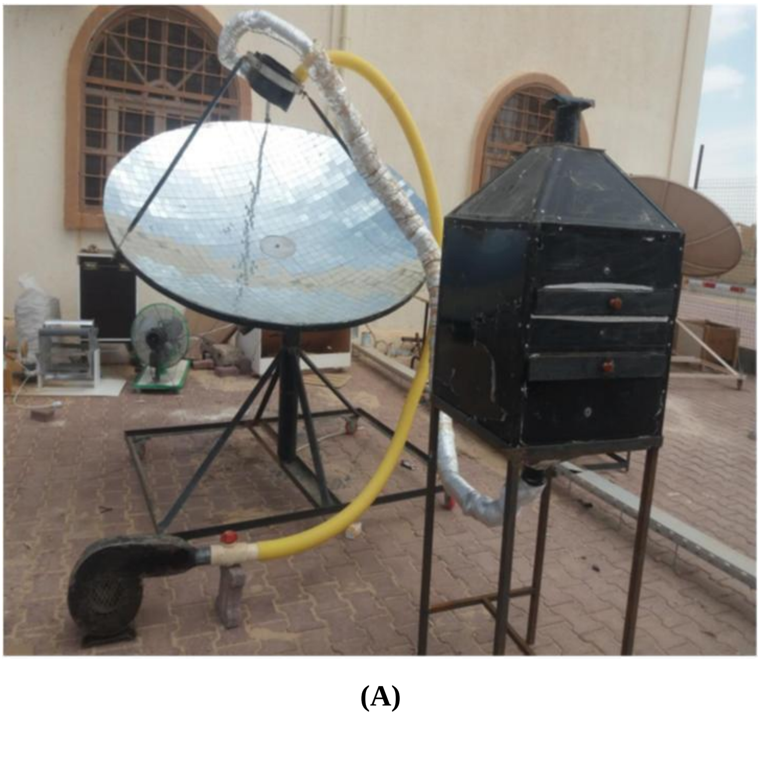
Where MR_{exp} and $MR_{pré}$ are, respectively, the water content from the experiment and predicted by the model, N is the number of observations, n is the number of model constants Statistical and correlation analysis and regression methods are widely used in modeling the behavior during drying of various agricultural products. Linear and non-linear regression models are essential to establish a relationship between variables and are of primary importance in case the authors have not established empirical relationships.

IV.1.2.3 Design of dryer improvement

Solar dryer assisted by concentrator design was divided into two major parts, air collector and main concentrator. Air collector cabinet was fabricated from iron steel with cylindrical shape as depicted in **Figure IV-11** To get exposure to sunlight for whole day with maximum intensity, several improvements in air collector unit was tested for increasing the temperature by adding different materials or increasing exchange surface.

2.1 Experimental drying of Groundnut using ISDPSDC filled by turning chip in the receiver

The effect of adding turning chip in the receiver was tested in the drying of groundnut under El Oued climate region.



(A)

7

(B) **(C)**

Figure IV-11 (A) Solar dryer assisted by dish concentrator. (B) Air collector. (C) Metal shavings.

The variation of moisture content and drying rate of groundnut is presented in **Figure IV-12** and **Figure IV-13**. As shown in theses results, the drying steps took place in 3 phases. The surface of the material to be dried in 0–200 min comes into equilibrium with the hot drying air. The phase of 200–600 min represents the 2nd stage where drying happens at a nearly constant rate. At this phase, the liquid was saturated the dried surface. During this period, the humidity of the surface cannot reach the evaporating humidity amount. After 600 min, the process starts to drop and the drying rate continued decreasing. After this point, when the drying process is continued, the temperature of the drying surface starts to increase. After 1000 min, the mass change of the groundnut stopped and the required moister content was reached. As can be observed from the drying rate with moisture content graph shown in **Figure IV-12**, the groundnut was dried from the initial moisture content of 0.9 g water/g dry matter to the final moisture content of 0.1 g water/g dry matter. When the drying rate with moisture content change is analyzed, it is seen a quite rapidly of the drying process at the beginning. After that begin to decrease, the reason is the rapid removal of free wetness on the groundnut together with the hot drying air. Around the end of the drying period, the amount of change in moisture decreased.

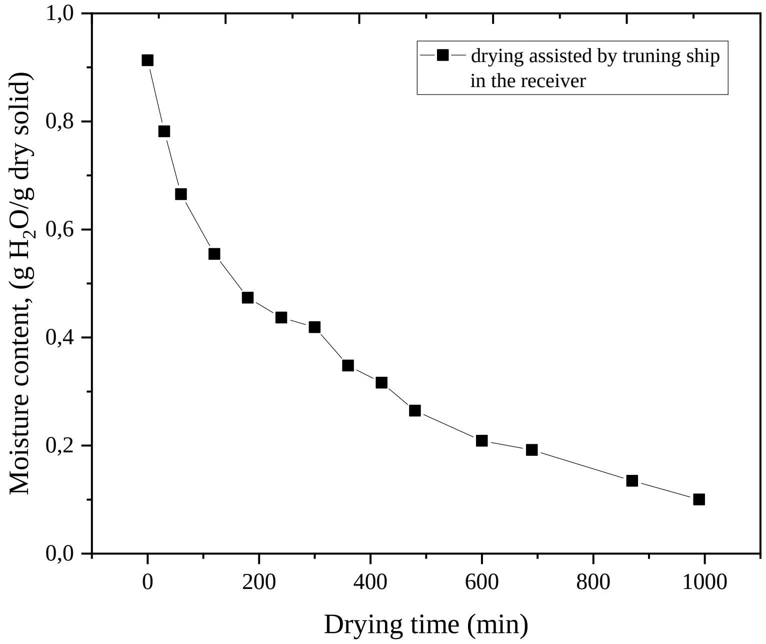


Figure IV-12 Variation of moisture content with drying time of groundnut samples dried by with a turning chip dryer

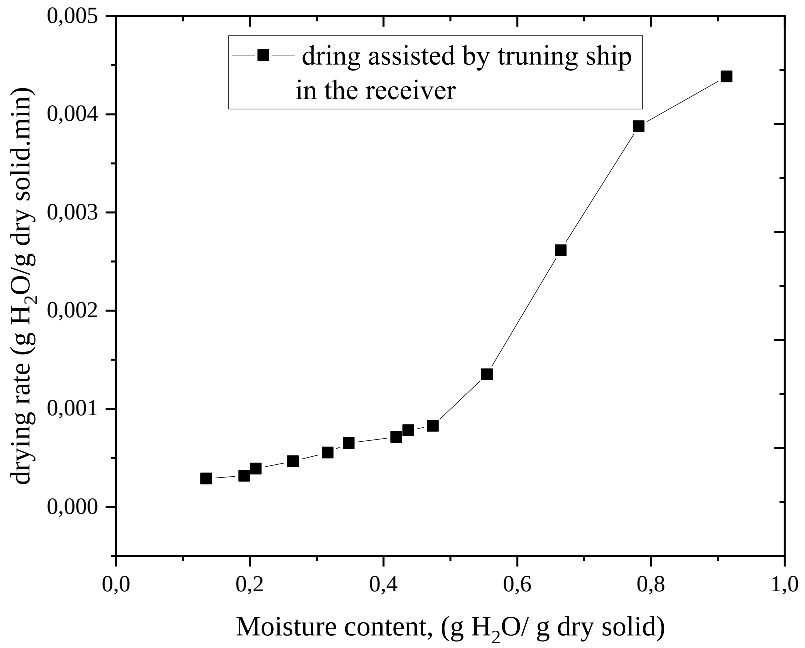
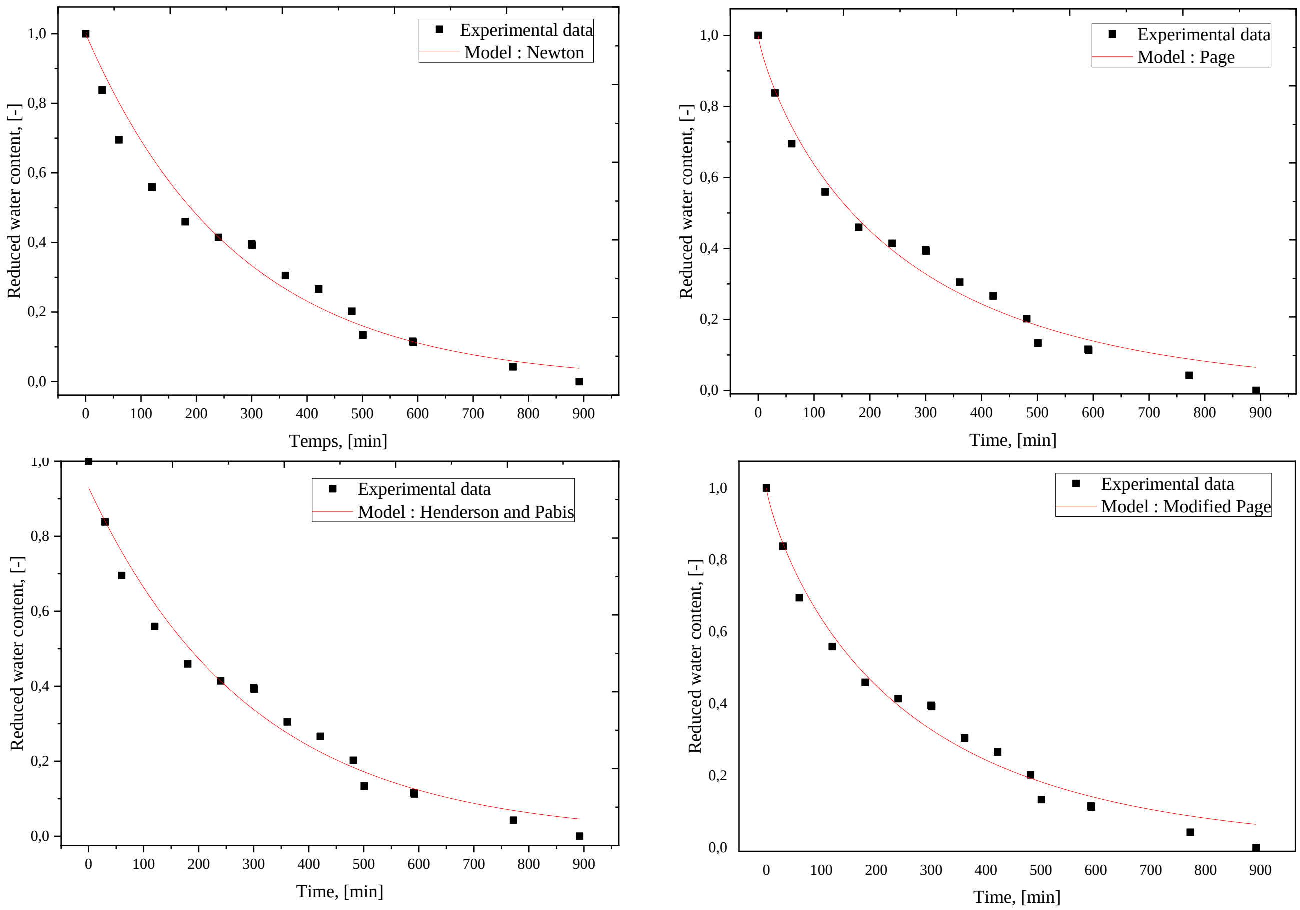


Figure IV-13 The influence of drying temperatures on the variation of the drying rate with moisture content of groundnut samples dried by with a turning chip dryer

The drying rate with moisture content of groundnut samples dried by with a turning chip dryer

Data of moisture content with drying time were predicted by several models of thin layer drying as in **Table IV. 1**, and these models are used very widely to describe the drying kinetics of most foods. The correlation coefficient (R^2) and chi-square (x^2) are among the most important criteria determining the suitability of the mathematical model.

Table IV. 2 shows the empirical constants and statistical results obtained from modeling different thin-layer equations when potatoes were dried at three different temperatures using the "Origin Pro 9.0" program. From the results, we note that the correlation coefficient (R^2) was not less than 0.96248, which confirms that the ten selected models were very close. The higher value of the correlation coefficient (R^2) for the mathematical model is the best way to describe the change in moisture content with drying time. It is worth noting that the rate draying pass from 47 to 9% moisture content.



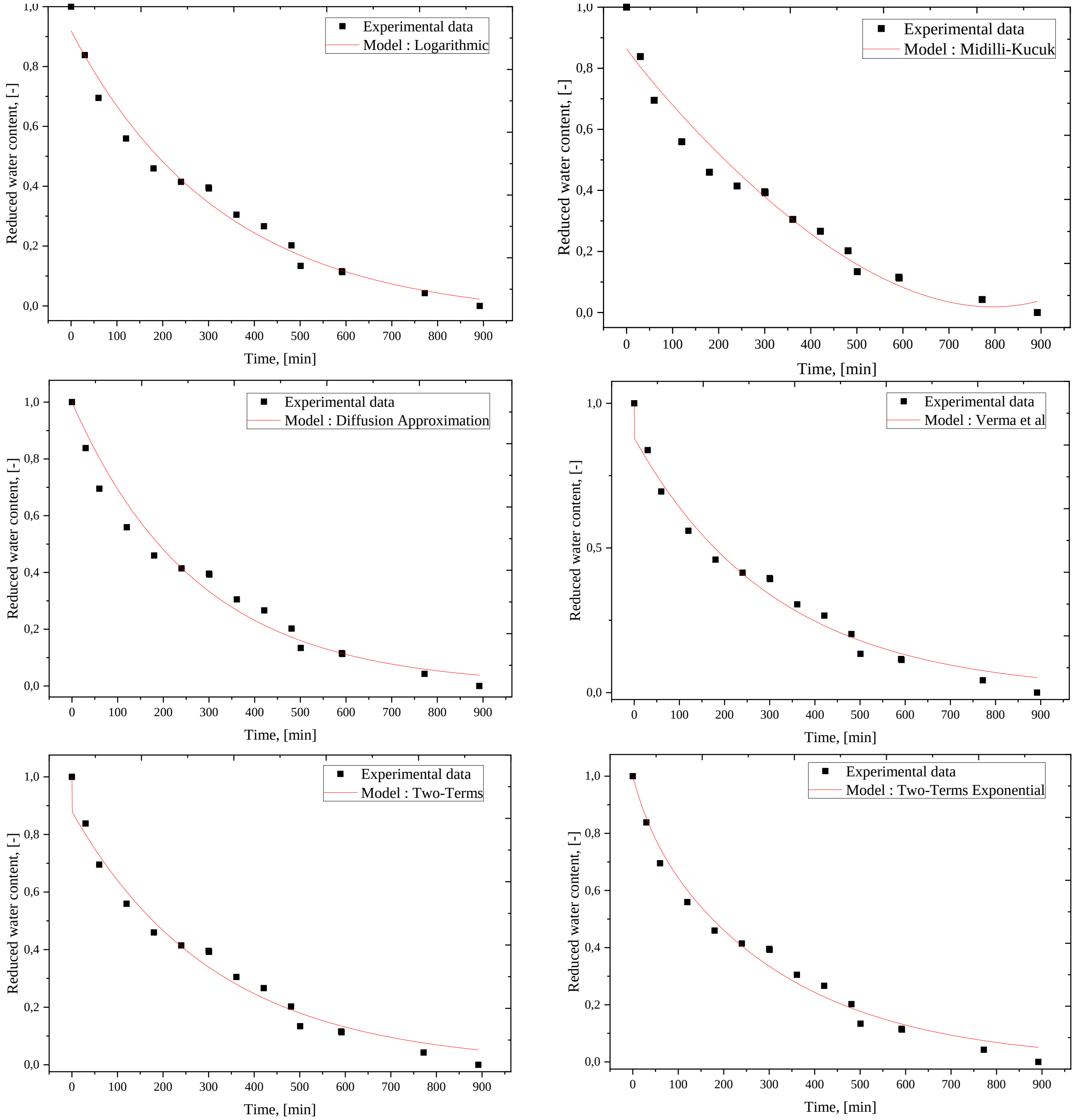


Figure IV-14 Graphs showing from different thin layer drying models for groundnut, and that assisted by turning chip in the receiver

Through the **Table IV. 2**, We obtained the best values when using the Verma et al model, where the value of the correlation parameters was 0.98358, the Chi-square value of 0.0015 and the root mean square error of 0.0396, and from it we conclude that the best mathematical model in describing the kinetics of drying groundnut assisted by turning chip in the receiver is the Verma et al. model.

Table IV. 2 Statistical results obtained from different thin layer drying models for groundnut assisted by turning chip in the receiver.

System	*N°*	*Models*	*Model constants*						R^2	*RMSE*	x^2
			K_1	K_2	*n*	*A*	*b*	*C*			
Drying assisted by turning chip in the receiver	01	Newton	0.0036						0.96736	0.052	0.0027
	02	Page	0.0101		0.8230				0.97917	0.043	0.0018
	03	HendersonandPabis	0,0081			0.9294			0.97674	0.0454	0.0020
	04	ModiedPage	0.0038		0.8252				0.97917	0.0429	0.0018
	05	Logarithmic	0.0030			0.9608		-0.041	0.97777	0.0460	0.0021
	06	Midilli-Kucuk	-2.72085E-4		1.2004	0.86407	-0.00246		0.96248	0.06232	0.00388
	07	DiffusionApproximation	0.00366			2.5617 E7	1		0.96736	0.0558	0.0031
	08	**Verma et al**	**7.5**	**0.0032**		**0.1198**			**0.98358**	**0.0396**	**0.0015**
	09	Two-Terms	0.00318	1.6068 E11		0.8802	0.1198		0.98358	0.041	0.0017
	10	Two-TermsExponential	0.02449			0.12993			0.98255	0.0393	0.1299

The comparison between the three enhancements of received unity and open sun drying is depicted in Erreur ! Source du renvoi introuvable.**Figure IV-15.** To ensure repeatability and reliability of experimental values, and to test the added value of the realized dryer, four set of experimental trials were done with the open sun and proposed enhanced drying during 17-18 November 2021. The required moisture ratio was achieved in less time for drying system that uses Indirect Solar Dryer using parabolic solar dish concentrator compared to open sun drying. Furthermore, it can see that the drying process is more quickly using ISDPDC with the received unity filled with fins. Hence it can be concluded that the enhancement in ISDPDC dryer is very interesting in order to fabricate one at industrial scale. Furthermore, the realized ISDPDC can help the farmers to preserve their crop products from any problem may be happen during the harvesting seasons.

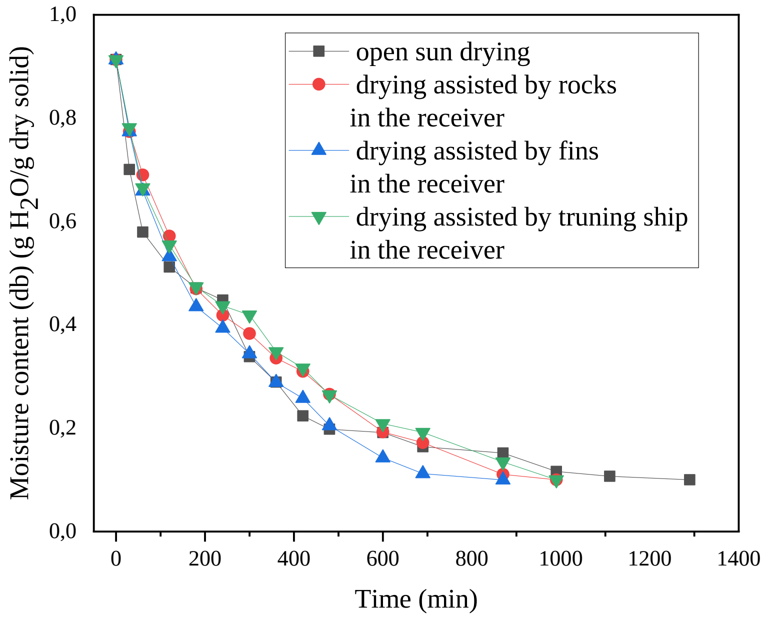


Figure IV-15 Variation of moisture content with drying time of groundnut samples dried by different techniques of enhancements

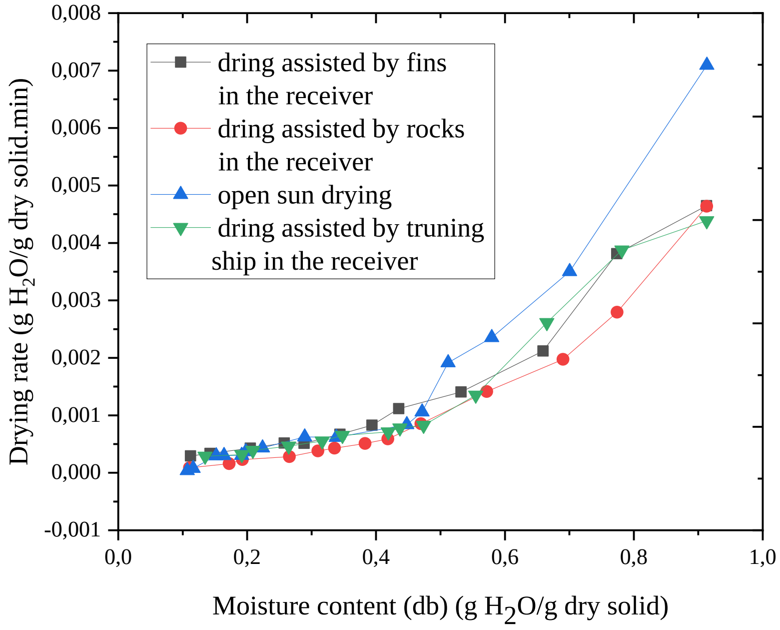


Figure IV-16 The influence of drying temperatures on the variation of the drying rate with moisture content of groundnut samples dried by different techniques of enhancements.

General Conclusion

As it is well known, Solar drying is one of the oldest applications of solar energy. It was used by the human mainly for food preservation but also for drying other useful materials as cloths, construction materials, etc.

As it was well exhibited in Chapter II Solar drying has not yet widely made saleable. Solar dryers are equipment, generally of small dimensions and based rather on empirical and semi-empirical data than in theoretical designs. The majority of the available solar dryer designs, are used mainly for drying of various crops either for family use or for small-scale industrial production.

Solar drying is one of the most fundamentals processes which allow increasing efficiently the storage time of the agro-alimentary products. This explains the numerous research studies that carried out in recent years for improving indirect solar dryers, which have proposed a set of innovative solution in this area such as the use of supplementary resource of energy supply, integration of phase change materials, etc.

For improving solar drying technology, An indirect type solar dryer assisted by parabolic dish concentrator was designed and realized in this work. This solar dryer was tested during the wind period under arid zone climate condition at laboratory, southeast of Algeria. The following findings were concluded based on the red chilli and peanuts drying experiments:

For the red chilli

- The mean solar radiation intensity throughout drying process of red chilli was detected around 440 W/m2.
- The medium ambient temperature and drying temperatures at tray during the drying experiments were 30 °C and 50 °C, respectively.
- The moisture content in the dryer red chilli decreased by 90% within 5 hours.
- The conditions inside the dryer (temperature and moisture content) were ideal for drying red chilli. In most solar dryers, drying the samples down to a safe moisture content about 10% water basis (wb) takes more than a day. Meanwhile, 5 hours were enough for drying red chilli using the parabolic dish concentrator solar dryer.

For the peanuts:

The temperature in the drying chamber reached an impressive 55°C with a drying time of 5 hours, while the drying degree, i.e., the moisture content, reduced from 47% to 9% for peanuts

According to the obtained results, the integrated drying unit can contribute considerably to realize efficient macroscale solar dryer in the future. However, it is noted that the parabolic dish concentrator solar dryer needs further research on the influence of all affecting parameters for practical industrial applications in the agriculture products domaine.

Annexes

Annex A: Experimental drying of Groundnut using ISDPSDC **filled by rocks in the receiver**

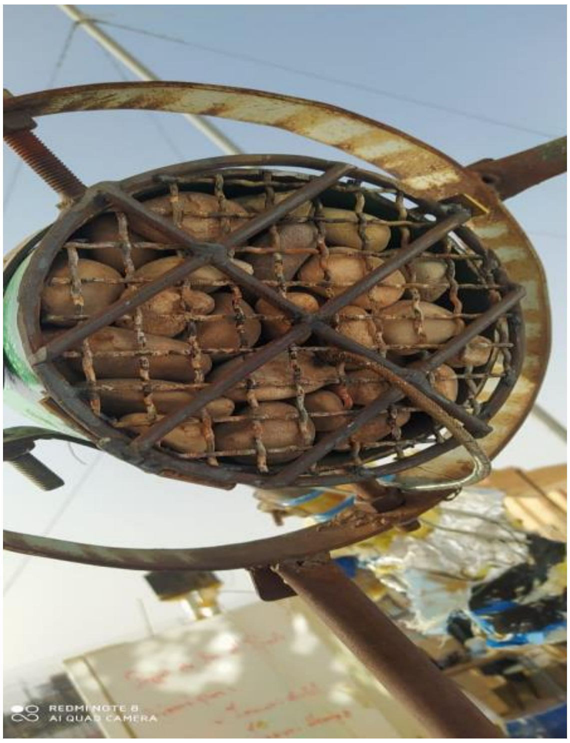


Figure 1. receiver filled by rocks

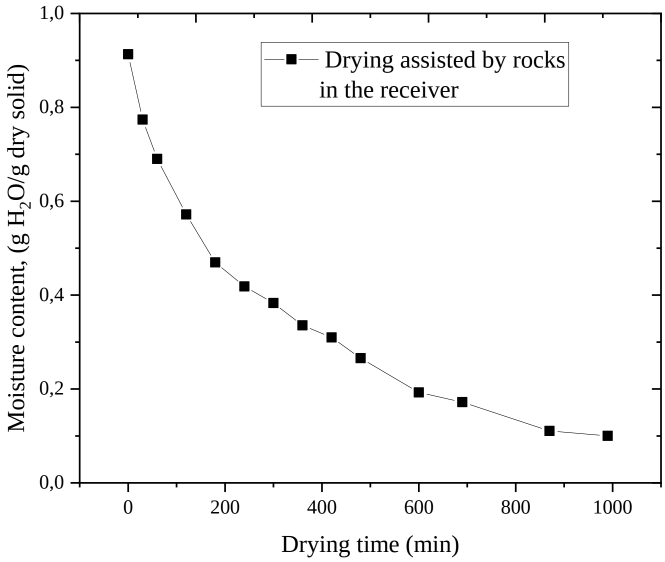


Figure 2. Variation of moisture content with drying time of groundnut samples dried by with a rock's dryer

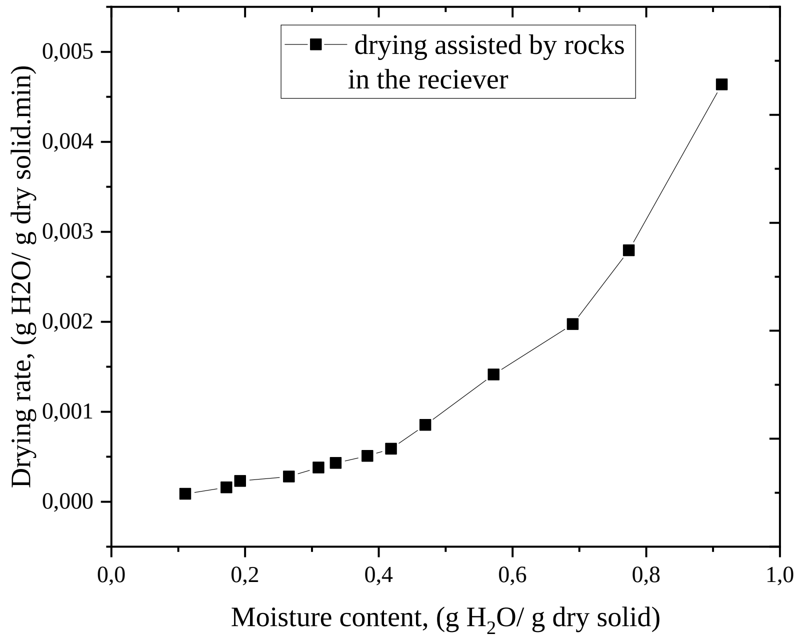
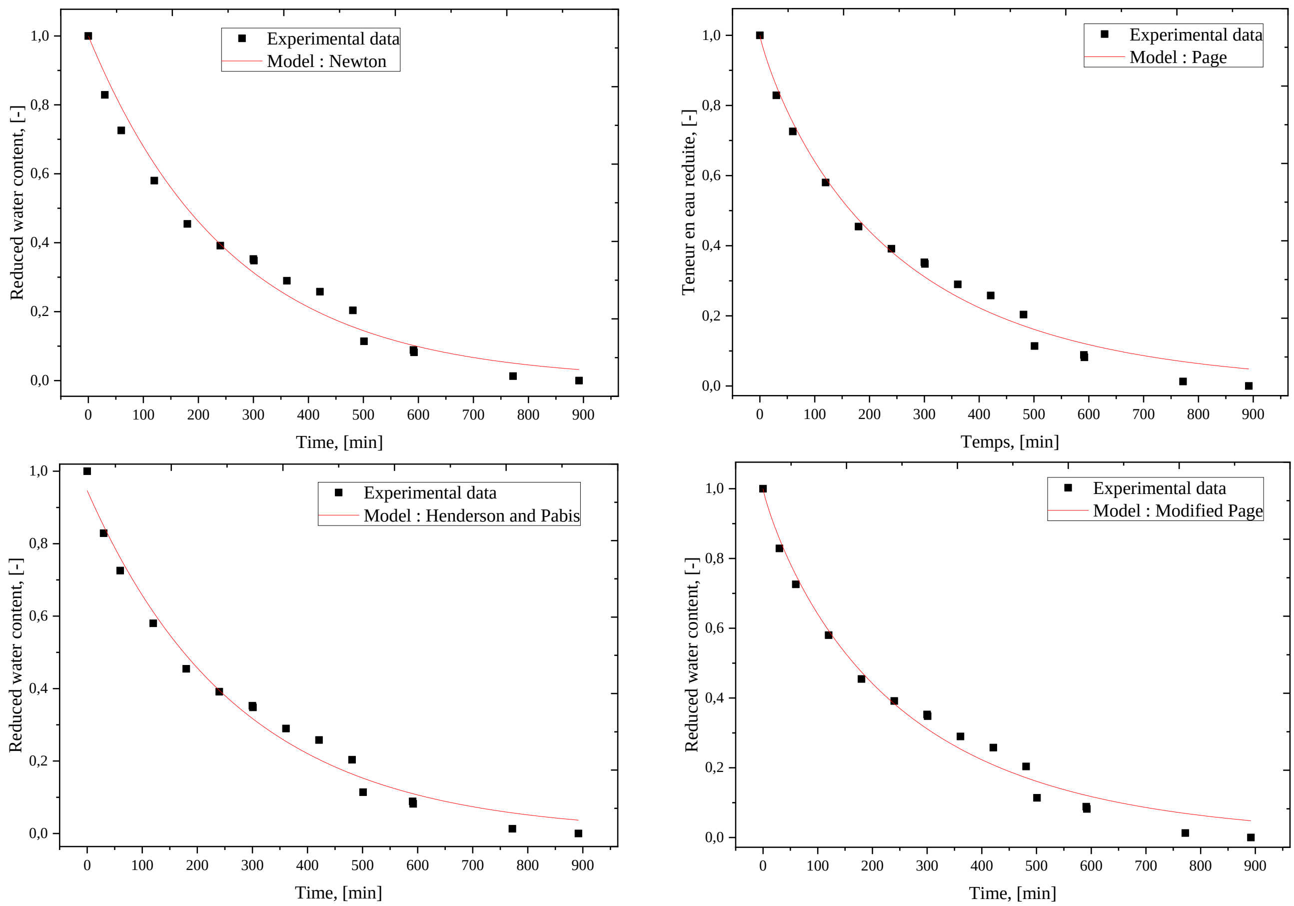


Figure 3. The influence of drying temperatures on the variation of the drying rate with moisture content of groundnut samples dried by with a rock's dryer



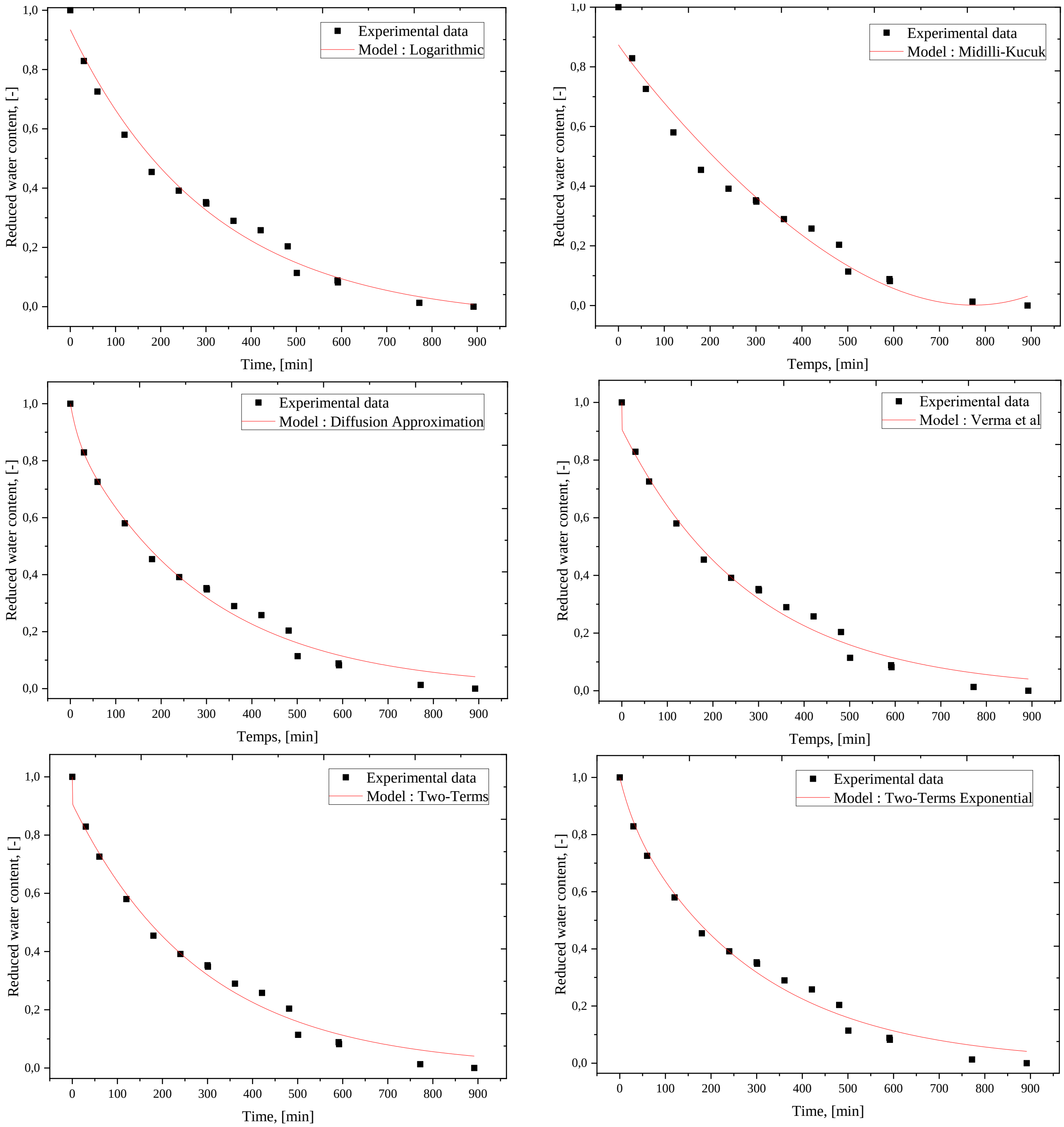


Figure 4. Modelling drying curves for the second sample (drying assisted by rocks in the receiver)

Table 1. Statistical results obtained from different thin layer drying models for groundnut assisted by rocks in the receiver.

System	*N°*	*Models*	*Model constants* K_1	K_2	*n*	*A*	*b*	*C*	R^2	*RMSE*	x^2
Drying assisted by rocks in the receiver	01	Newton	0.0038						0.97945	0.04258	0.00181
	02	Page	0.00794		0.87463				0.98469	0.03804	0.00145
	03	Henderson and Pabis	0.00364			0.94693			0.98429	0.03853	0.00148
	04	Modied Page	0.00397		0.87684				0.98469	0.03804	0.00145
	05	Logarithmic	0.00322			0.98264		-0.0481	0.9859	0.03789	0.00144
	06	Midilli-Kucuk	-2.77596E-4		1.20329	0.87391	-0.00259		0.96994	0.05758	0.00332
	07	**Diffusion Approximation**	**0.0566**			**0.10528**	**0.06067**		**0.98816**	**0.03471**	**0.0012**
	08	Verma et al	0.00348	7		0.90755			0.90755	0.03493	0.00122
	09	Two-Terms	0.00348	5		0.90755	0.09245		0.09245	0.03636	0.00132
	10	Two-Terms Exponential	0.03218			0.10707			0.9877	0.0341	0.00116

Annex B: Experimental drying of Groundnut using ISDPSDC filled by fins in the receiver

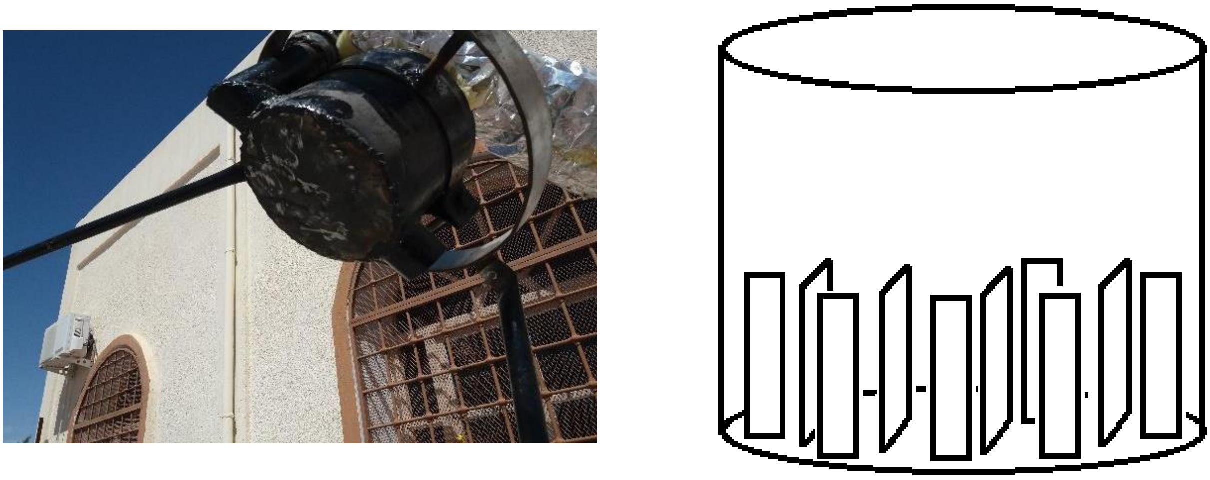


Figure 5. receiver filled by fins

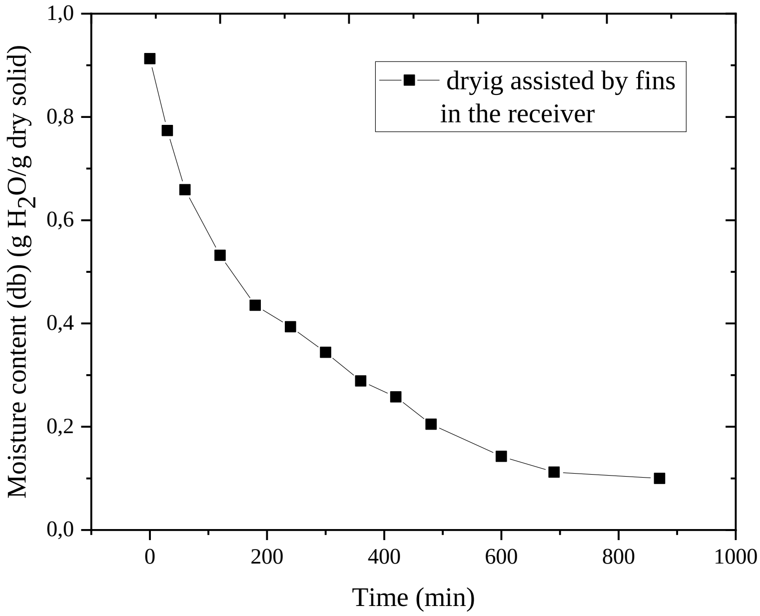


Figure 6. Variation of moisture content with drying time of groundnut samples dried by with a fin's dryer

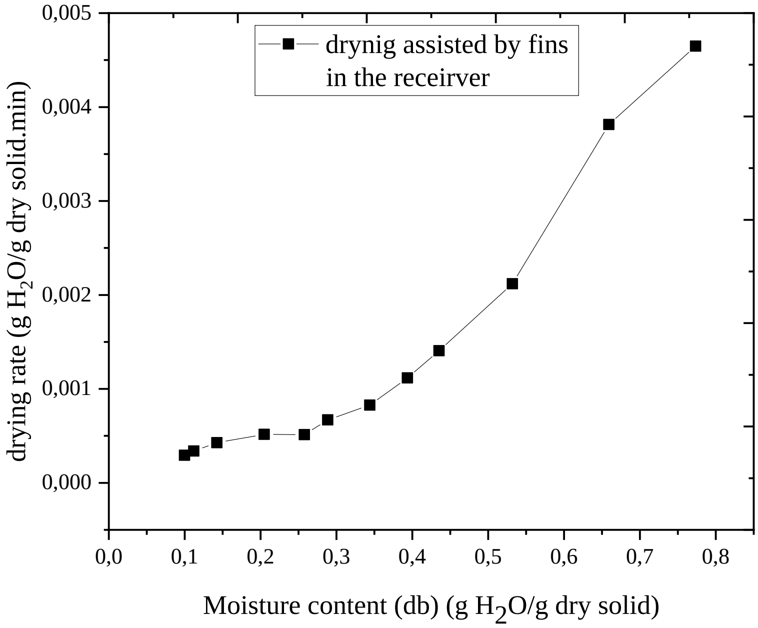
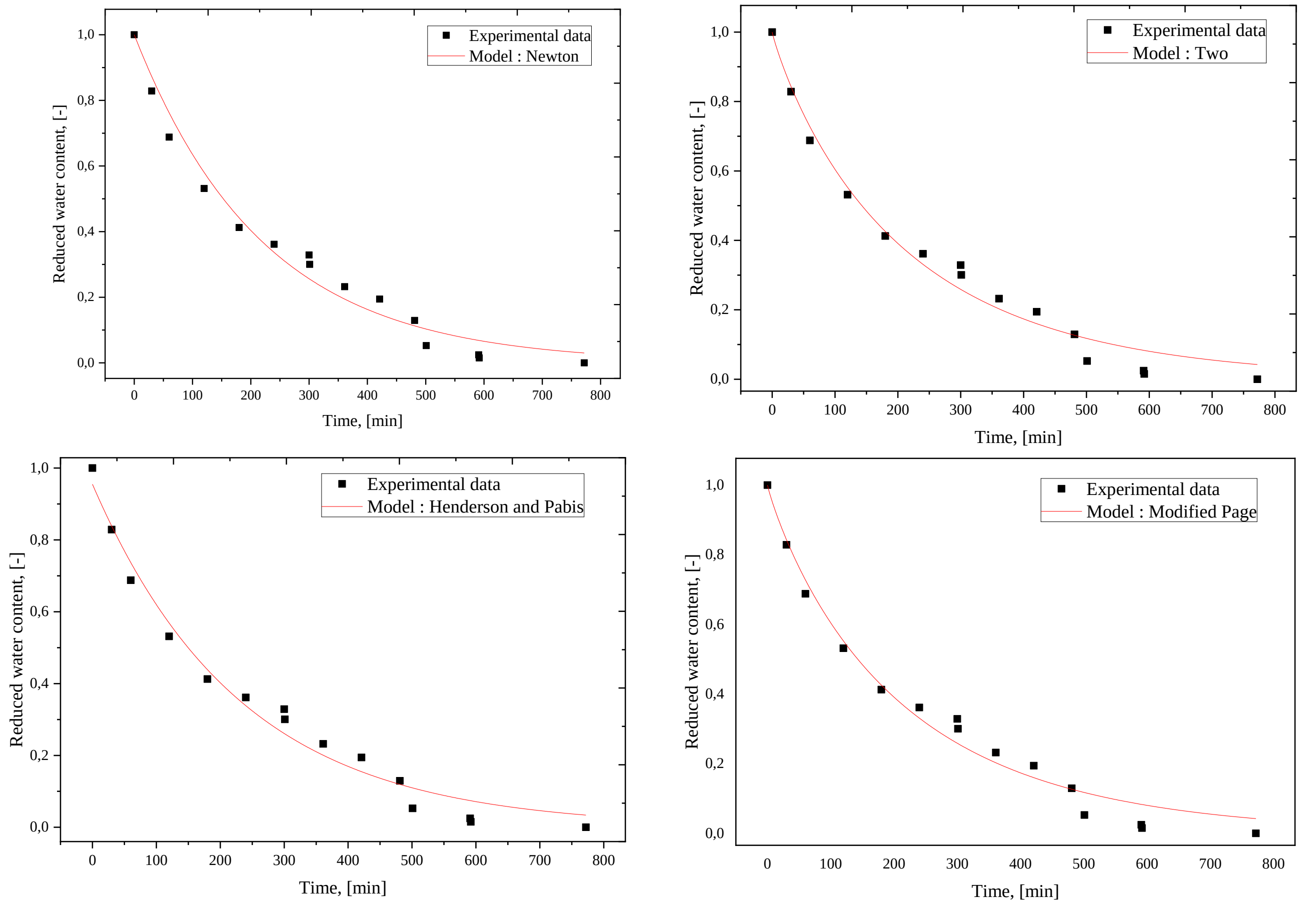


Figure 7. The influence of drying temperatures on the variation of the drying rate with moisture content of groundnut samples dried by with a fins dryer



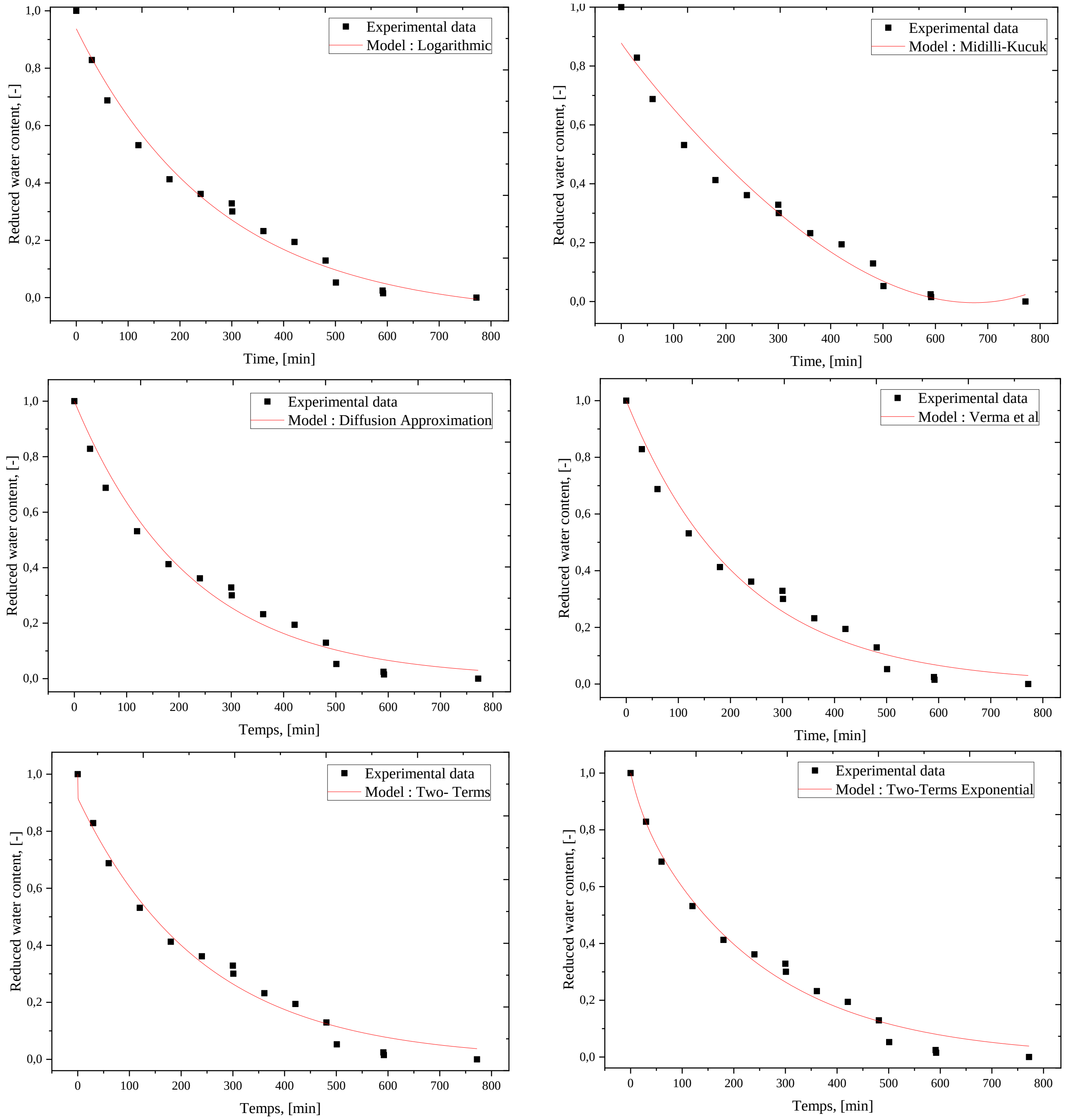


Figure 8. Modelling drying curves for the third sample (drying assisted by fins in the receiver)

Table 2. Statistical results obtained from different thin layer drying models for groundnut assisted by fins in the receiver.

System	*N°*	*Models*	*Model constants*						*R^2*	*RMSE*	*x^2*
			K_1	*K_2*	*n*	*A*	*b*	*C*			
Drying assisted by fins in the receiver	01	Newton	0.0045						0.97686	0.0467	0.00218
	02	Page	0.00803		0.8986				0.98023	0.04481	0.00201
	03	HendersonandPabis	0.00432			0.95497			0.9801	0.04495	0.00202
	04	ModiedPage	0.00466		0.89869				0.98023	0.04481	0.00201
	05	Logarithmic	0.00364			1.00342		-0.065	0.98296	0.04329	0.00187
	06	Midilli-Kucuk	-3.16102E-4		1.20864	0.87813	-0.00299		0.96969	0.06031	0.00364
	07	DiffusionApproximation	0.00454			-138609.952	1		0.97686	0.05044	0.00254
	08	Vermaetal	0.00454	0.00453		0.97988			0.97686	0.05044	0.00254
	09	Two-Terms	0.00414	5		0.91634	0.08366		0.98296	0.04521	0.00204
	10	Two-TermsExponential	**0.00204**			**0.10213**			**0.98319**	**0.04131**	**0.00171**

Annex C: Experimental drying of Groundnut in open sun

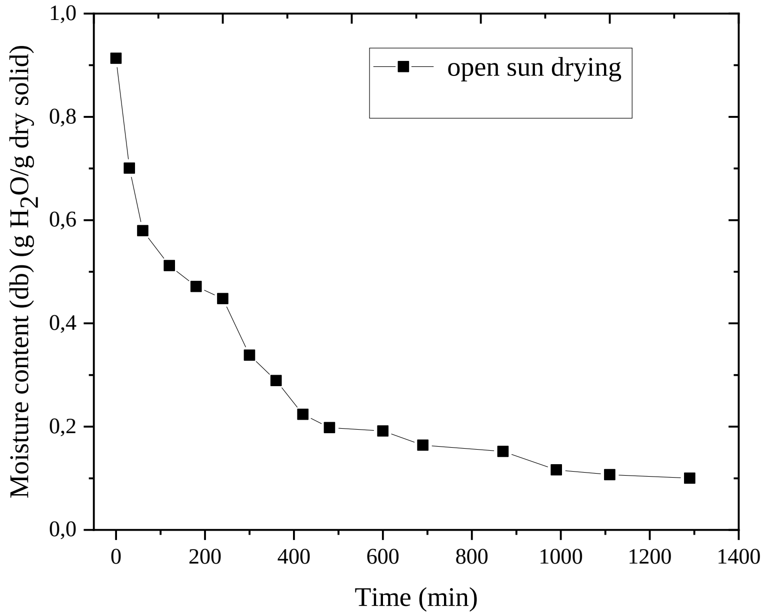


Figure 9. Variation of moisture content with drying time of groundnut in open sun

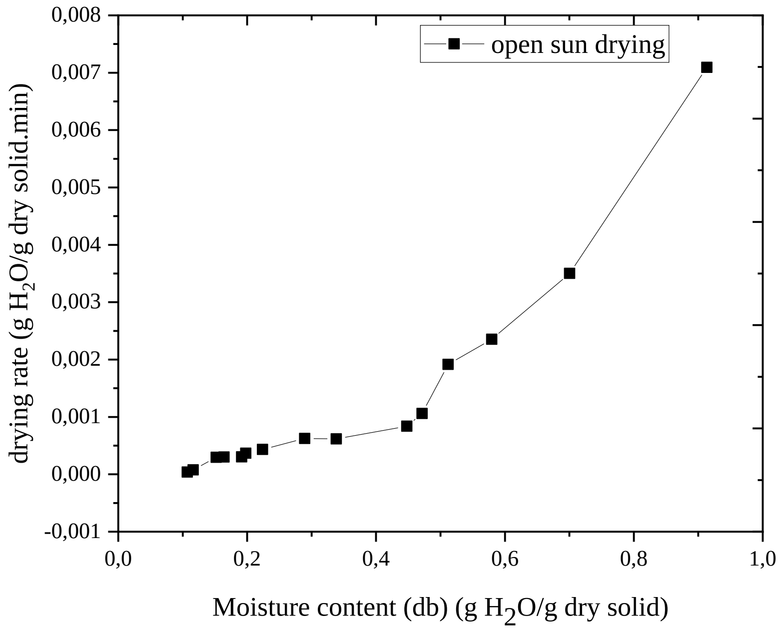
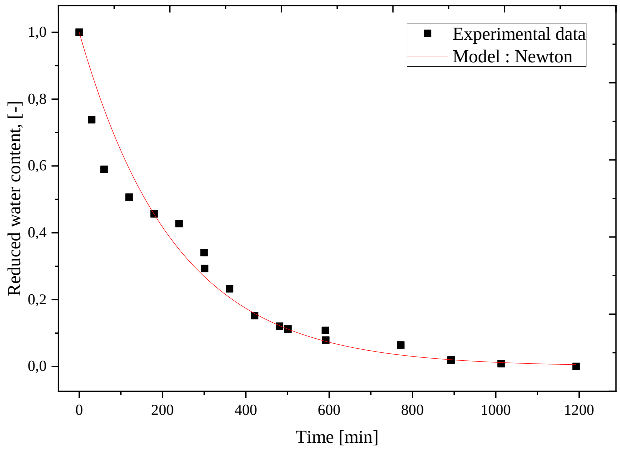
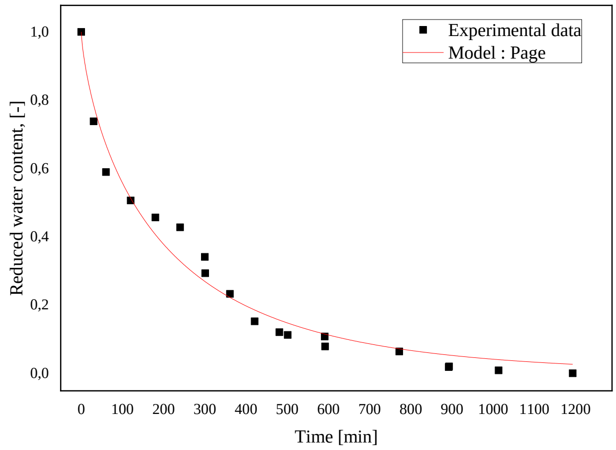
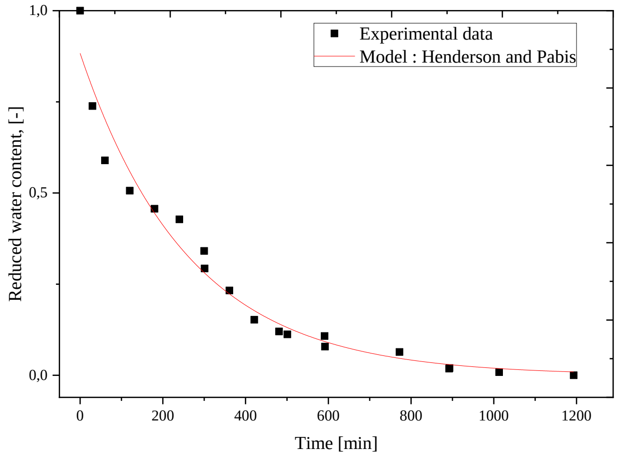
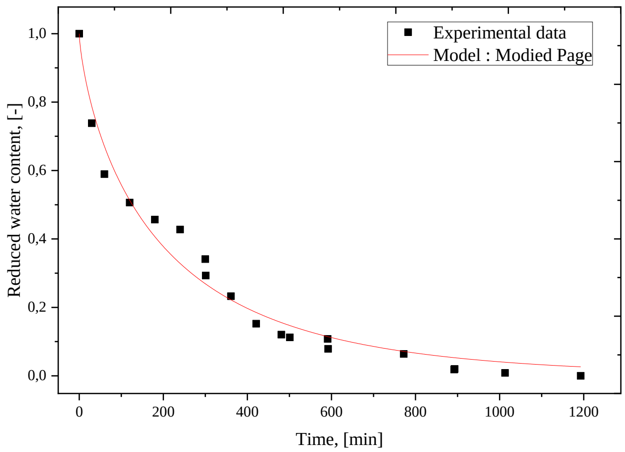


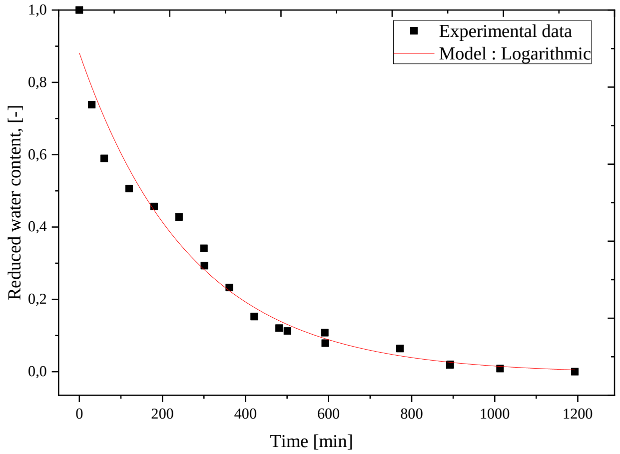
Figure 10. The influence of drying temperatures on the variation of the drying rate with moisture content of groundnut in open sun

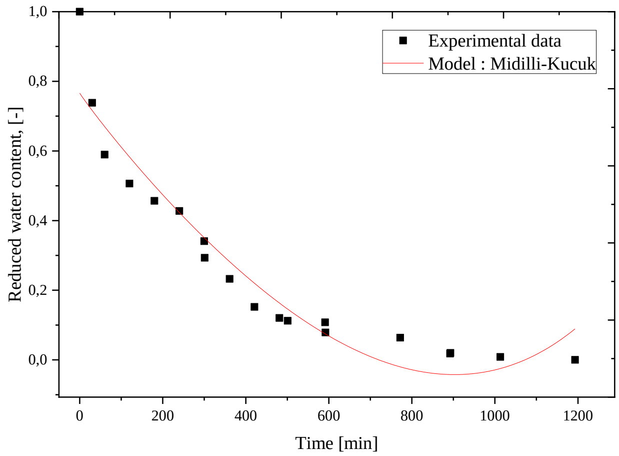

Experimental data
Model : Newton
Reduced water content, [-]
0,0
0,2
0,4
0,6
0,8
1,0
0
200
400
600
800
1000
1200
Time [min]

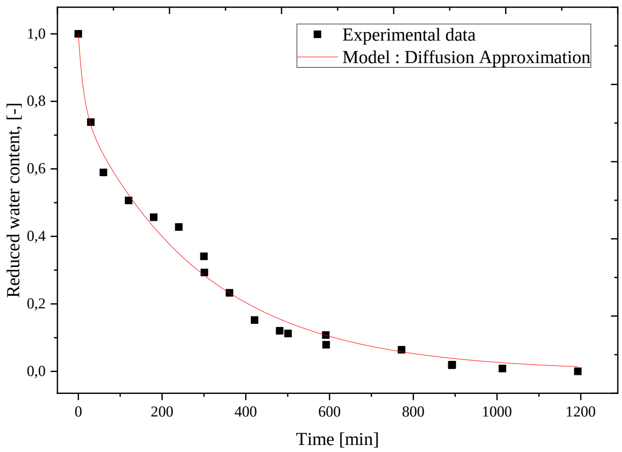

Experimental data
Model : Page
Reduced water content, [-]
0,0
0,2
0,4
0,6
0,8
1,0
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
Time [min]

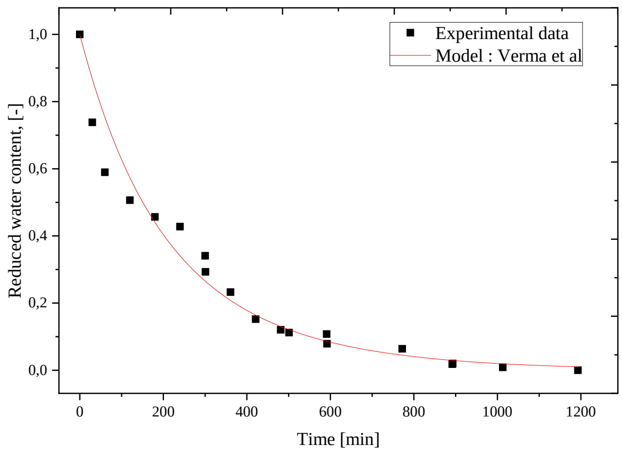

Experimental data
Model : Henderson and Pabis
Reduced water content, [-]
0,0
0,5
1,0
0
200
400
600
800
1000
1200
Time [min]


Experimental data
Model : Modied Page
Reduced water content, [-]
0,0
0,2
0,4
0,6
0,8
1,0
0
200
400
600
800
1000
1200
Time, [min]


Experimental data
Model : Logarithmic
Reduced water content, [-]
0,0
0,2
0,4
0,6
0,8
1,0
0
200
400
600
800
1000
1200
Time [min]


Experimental data
Model : Midilli-Kucuk
Reduced water content, [-]
0,0
0,2
0,4
0,6
0,8
1,0
0
200
400
600
800
1000
1200
Time [min]


Experimental data
Model : Diffusion Approximation
Reduced water content, [-]
0,0
0,2
0,4
0,6
0,8
1,0
0
200
400
600
800
1000
1200
Time [min]


Experimental data
Model : Verma et al
Reduced water content, [-]
0,0
0,2
0,4
0,6
0,8
1,0
0
200
400
600
800
1000
1200
Time [min]

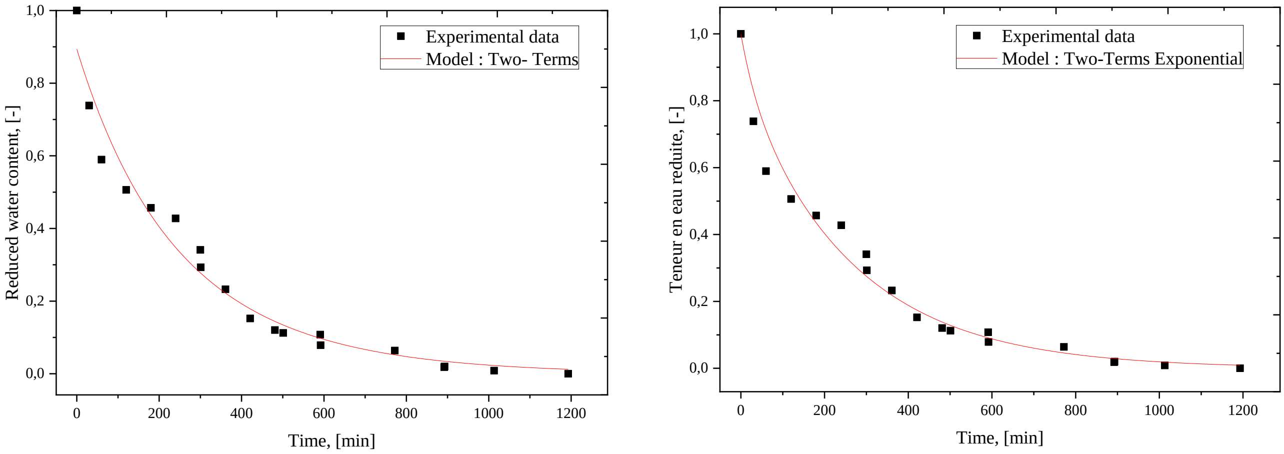


Figure 11. Modelling drying curves for the fourth sample (drying in open sun)

Table 3. Statistical results obtained from different thin layer drying models for groundnut in the open sun.

System	*N°*	*Models*	*Model constants*						R^2	*RMSE*	x^2
			K_1	K_2	*n*	*A*	*b*	*C*			
Drying in the open air	01	Newton	0.0043						0.94798	0.06382	0.00407
	02	Page	0.01962		0.73696				0.97441	0.04606	0.00212
	03	HendersonandPabis	0.00381			0.88297			0.96909	0.05063	0.00256
	04	ModiedPage	0.00256		0.73891				0.97441	0.04606	0.00212
	05	Logarithmic	0.00375			0.88642		-0.005	0.96915	0.05213	0.00272
	06	Midilli-Kucuk	-3.6731E-4		1.14548	0.76587	-0.00212		0.92374	0.08465	0.00717
	07	**DiffusionApproximation**	**0.07955**			**0.21588**	**0.04236**		**0.98644**	**0.03456**	**0.00119**
	08	**Vermaetal**	**0.00337**	**0.07969**		**0.78427**			**0.98644**	**0.03456**	**0.00119**
	09	Two-Terms	0.07967	0.00337		0.21627	0.78417		0.98645	0.03569	0.00127
	10	Two-TermsExponential	0.14033			0.02706			0.97196	0.04822	0.00232

Publications dans le cadre de cette thèse

Publication

- **Realization of a Solar Dryer Assisted by a Parabolic Dish Concentrator,** *Defect and Diffusion Forum, ISSN: 1662-9507, Vol. 406, pp 192-199, doi:10.4028/www.scientific.net/DDF.406.192*

Communications

- **Réalisation d'un séchoir solaire assiste par un concentrateur parabolique,** *7th SMSTS 2019, 14-15-16 Novembre 2019, Marrakech-Maroc.*

Bibliographies

[1] A. Benhamza *et al.*, "Multi-objective design optimization of solar air heater for food drying based on energy, exergy and improvement potential," vol. 169, pp. 1190-1209, 2021.
[2] M. Lati *et al.*, "Experimental investigation on effect of an absorber plate covered by a layer of sand on the efficiency of passive solar air collector," vol. 16, no. 6, pp. 413-422, 2019.
[3] A. Sanghi, R. K. Ambrose, and D. J. D. t. Maier, "CFD simulation of corn drying in a natural convection solar dryer," vol. 36, no. 7, pp. 859-870, 2018.
[4] M. Sandali, A. Boubekri, D. Mennouche, and N. J. R. E. Gherraf, "Improvement of a direct solar dryer performance using a geothermal water heat exchanger as supplementary energetic supply. An experimental investigation and simulation study," vol. 135, pp. 186-196, 2019.
[5] P. Talbot, M. Lhote, C. Heilporn, A. Schubert, F.-X. Willaert, and B. J. D. T. Haut, "Ventilated tunnel solar dryers for small-scale farmers communities: Theoretical and practical aspects," vol. 34, no. 10, pp. 1162-1174, 2016.
[6] M. Ndukwu, M. Simo-Tagne, F. Abam, O. Onwuka, S. Prince, and L. J. H. Bennamoun, "Exergetic sustainability and economic analysis of hybrid solar-biomass dryer integrated with copper tubing as heat exchanger," vol. 6, no. 2, p. e03401, 2020.
[7] M. Ndukwu, L. Bennamoun, and F. J. F. E. R. Abam, "Experience of solar drying in Africa: presentation of designs, operations, and models," vol. 10, no. 4, pp. 211-244, 2018.
[8] A. Laouini, B. Benhaoua, K. Aoues, and A. Atia, "Realization of a Solar Dryer Assisted by a Parabolic Dish Concentrator," in *Defect and Diffusion Forum*, 2021, vol. 406: Trans Tech Publ, pp. 192-199.
[9] V. Kumar, B. Singh, C. S. Samsher, and S. Singh, "A review on tomato drying by different methods with pretreatments," *International Journal of Food and Fermentation Technology*, vol. 5, no. 1, pp. 15-24, 2015.
[10] A. Saxena, I. Dutta, and S. Bhansali, "Is there a need for national guidance on pregnancy after bariatric surgery? An interesting case report," in *BJOG-AN INTERNATIONAL JOURNAL OF OBSTETRICS AND GYNAECOLOGY*, 2017, vol. 124: WILEY 111 RIVER ST, HOBOKEN 07030-5774, NJ USA, pp. 93-93.
[11] A. B. Bosworth, "The historical setting of Megasthenes' Indica," *Classical Philology*, vol. 91, no. 2, pp. 113-127, 1996.
[12] V. Belessiotis and E. Delyannis, "Solar drying," *Solar energy*, vol. 85, no. 8, pp. 1665-1691, 2011.
[13] K. Kröll, "Trocknen und Trockner in der Produktion," p. 632 April 1989.
[14] A. CHARREAU and R. CAVAILLE, "Séchage: I. Théorie et calculs," *Techniques de l'ingénieur. Génie des procédés*, vol. 2, pp. J24080. 1-J2480. 23, 1991.
[15] S. Boughali, "Etude et optimisation du sechage solaire des produits agro-alimentaires dans les zones arides et desertiques," Université de Batna 2, 2010.
[16] K. Kabidi, "Experimentation et modelisation du comportement energetique et thermique d’un sechoir solaire sous le climat de la region de Rabat," PhD Thesis, Universite Mohammed v–Agdal, 2014.
[17] K. Chua, S. Chou, J. Ho, and M. Hawlader, "Heat pump drying: Recent developments and future trends," *Drying technology*, vol. 20, no. 8, pp. 1579-1610, 2002.

[18] N. Bekkioui, "Séchage solaire du bois: Modélisation simplifiée du séchage d'une pile de bois dans un séchoir à parois vitrées," 2009.
[19] O. Prakash and A. Kumar, "Historical review and recent trends in solar drying systems," *International journal of green energy,* vol. 10, no. 7, pp. 690-738, 2013.
[20] A. Khyad, "Utilisation de l'énergie solaire dans le processus de séchage de la céramique," 2016.
[21] M. Bargach, "Étude expérimentale et modélisation du Comportement thermique des serres agricoles au Maroc. Application à la conception, la réalisation et filetest de fonctionnement d'un système de chauffage de serres agricoles par utilisation des capteurs solaires plans," Thèse de Doctorat, Faculté des sciences de Rabat, 2000.
[22] D. Luna Sanchez, "Modélisation et conception préliminaire d'un séchoir solaire pour bois de pin avec stockage d'énergie," Paris, ENSAM, 2008.
[23] A. Rabl, *Active solar collectors and their applications*. Oxford University Press on Demand, 1985.
[24] B. Touati, "Etude théorique et expérimentale du séchage solaire des feuilles de la menthe verte (Mentha viridis)," Lyon, INSA, 2008.
[25] S. Sharma, P. Nath, and B. Bali, "A solar timber seasoning kiln," *Journal of the Timber Development Association of India,* vol. 18, no. 2, 1972.
[26] D. Prestemon, "Solar lumber drying," *Forestry Extension Notes, F-347., Article., Iowa State University Ames., USA,* 1983.
[27] B. H. Bond, "Design and operation of a solar-heated dry kiln," 2009.
[28] N. Berthomieu, "'fiche sur les différents types de séchoirs solaires a convection naturelle et forcee," *Deutsche Gesellschaft für Technische Zusammenarbeit GTZ (GmbH),* 2004.
[29] S. MANAA, "Analyse structurelle et conceptuelle des facteurs d'optimisation des performances des insolateurs plans munis d'ailettes pour des applications diverses en fonction des contextes géographiques et climatiques," Université Mohamed Khider-Biskra, 2017.
[30] W. T. Simpson, "Drying technology issues in tropical countries," 1992: IUFRO Nancy, France.
[31] T. G. Lumley, "Solar drying of wood in Louisiana," 1981.
[32] J. Bahraoui-Buret and A. Khtira, "Etude du rayonnement solaire à Rabat," *Revue Internationale d'héliotechnique, 2ème semestre,* pp. 7-11, 1984.
[33] T. Lumley and C. ET, "Technical and economic characteristics of two solar kiln designs," 1979.
[34] S. Bechis and F. Barigazzi, "Première publication, 2013."
[35] S. Bechis, "manuel de construction et utilisation du séchoir Icaro 2007."
[36] A. Villiere, "Drying of wood," *Drying of wood.,* no. 6th ed.(rev.), 1966.
[37] T. Swetman, "Séchage solaire," 2007.
[38] P. Joly, "Et More-Chevalier F," *Théorie, pratique et économique du séchage des bois, H. Vial,* 1980.
[39] A. Khadouri, "Le séchage du bois au Maroc, conception d'un séchoir solaire," *Mémoire de 3éme cycle agronomie, IVA Hassan II de Rabat,* 1986.
[40] C. Achberger *et al.*, "State of the climate in 2012," *Bulletin of the American Meteorological Society,* vol. 94, no. 8, pp. S1-S238, 2013.
[41] S. K. Amit, M. Uddin, R. Rahman, S. Islam, and M. S. Khan, "A review on mechanisms and commercial aspects of food preservation and processing," *Agriculture & Food Security,* vol. 6, no. 1, pp. 1-22, 2017.
[42] A. Karafil, H. Ozbay, M. Kesler, and H. Parmaksiz, "Calculation of optimum fixed tilt angle of PV panels depending on solar angles and comparison of the results

with experimental study conducted in summer in Bilecik, Turkey," in *2015 9th International Conference on Electrical and Electronics Engineering (ELECO)*, 2015: IEEE, pp. 971-976.

[43] W. P. Missana, E. Park, and T. T. Kivevele, "Thermal performance analysis of solar dryer integrated with heat energy storage system and a low-cost parabolic solar dish concentrator for food preservation," *Journal of Energy,* vol. 2020, 2020.

[44] N. Panwar, S. Kaushik, and S. Kothari, "State of the art of solar cooking: An overview," *Renewable and Sustainable Energy Reviews,* vol. 16, no. 6, pp. 3776-3785, 2012.

[45] A. Sharma, C. Chen, and N. V. Lan, "Solar-energy drying systems: A review," *Renewable and sustainable energy reviews,* vol. 13, no. 6-7, pp. 1185-1210, 2009.

[46] G. Babagana, K. Silas, and B. Mustafa, "Design and construction of forced/natural convection solar vegetable dryer with heat storage," *ARPN Journal of Engineering and Applied Sciences,* vol. 7, no. 10, pp. 1213-1217, 2012.

[47] M. Kumar, S. K. Sansaniwal, and P. Khatak, "Progress in solar dryers for drying various commodities," *Renewable and Sustainable Energy Reviews,* vol. 55, pp. 346-360, 2016.

[48] A. El-Sebaii, S. Aboul-Enein, M. Ramadan, and H. El-Gohary, "Experimental investigation of an indirect type natural convection solar dryer," *Energy conversion and management,* vol. 43, no. 16, pp. 2251-2266, 2002.

[49] H. Othieno, W. Grainger, and J. Twidell, "Application of small scale solar crop driers to maize drying in Kenya," in *Energy for rural and island communities*: Elsevier, 1982, pp. 377-386.

[50] B. Lamrani and A. Draoui, "Thermal performance and economic analysis of an indirect solar dryer of wood integrated with packed-bed thermal energy storage system: A case study of solar thermal applications," *Drying Technology,* vol. 39, no. 10, pp. 1371-1388, 2021.

[51] A. Bhardwaj, R. Kumar, and R. Chauhan, "Experimental investigation of the performance of a novel solar dryer for drying medicinal plants in Western Himalayan region," *Solar Energy,* vol. 177, pp. 395-407, 2019.

[52] A. Sözen, F. Ş. Kazancıoğlu, A. D. Tuncer, A. Khanlari, Y. C. Bilge, and A. Gungor, "Thermal performance improvement of an indirect solar dryer with tube-type absorber packed with aluminum wool," *Solar Energy,* vol. 217, pp. 328-341, 2021.

[53] M. A. Al-Neama and I. Farkas, "Thermal efficiency of vertical and horizontal-finned solar collector integrated with forced air circulation dryer for Apple as a sample," *Drying technology,* vol. 37, no. 5, pp. 546-558, 2019.

[54] M. Iranmanesh, H. S. Akhijahani, and M. S. B. Jahromi, "CFD modeling and evaluation the performance of a solar cabinet dryer equipped with evacuated tube solar collector and thermal storage system," *Renewable Energy,* vol. 145, pp. 1192-1213, 2020.

[55] S. Salve and A. Fulambarkar, "A solar dryer for drying green chili in a forced convection for increasing the moisture removing rate," *Materials Today: Proceedings,* vol. 45, pp. 3170-3176, 2021.

[56] P. X. Mutabilwa and K. N. Nwaigwe, "Experimental evaluation of drying of banana using a double-pass solar collector (DPSC) and theoretical analysis using a CFD model," *Cogent Engineering,* vol. 7, no. 1, p. 1789363, 2020.

[57] A. El Khadraoui, S. Bouadila, S. Kooli, A. Farhat, and A. Guizani, "Thermal behavior of indirect solar dryer: Nocturnal usage of solar air collector with PCM," *Journal of cleaner production,* vol. 148, pp. 37-48, 2017.

[58] N. Vigneshkumar *et al.*, "Investigation on indirect solar dryer for drying sliced potatoes using phase change materials (PCM)," *Materials Today: Proceedings,* vol. 47, pp. 5233-5238, 2021.

[59] A. Lingayat, V. Chandramohan, and V. Raju, "Design, development and performance of indirect type solar dryer for banana drying," *Energy Procedia,* vol. 109, pp. 409-416, 2017.

[60] W. Wang, M. Li, R. H. E. Hassanien, Y. Wang, and L. Yang, "Thermal performance of indirect forced convection solar dryer and kinetics analysis of mango," *Applied Thermal Engineering,* vol. 134, pp. 310-321, 2018.

[61] D. Parikh and G. Agrawal, "Solar drying in hot and dry climate of Jaipur," *International Journal of Renewable Energy Research,* vol. 1, no. 4, pp. 224-231, 2012.

[62] W. Saadeh, J. Haddad, and F. Anton, "Green Drying of Tomato Slices by Modified Indirect Air Solar Heater," *J. Chem. Eng. Japan,* vol. 51, no. 2, pp. 166-169, 2018.

[63] A. Fudholi, M. Y. Othman, M. H. Ruslan, and K. Sopian, "Drying of Malaysian Capsicum annuum L.(red chili) dried by open and solar drying," *International Journal of Photoenergy,* vol. 2013, 2013.

[64] H. Bhowmik and R. Amin, "Efficiency improvement of flat plate solar collector using reflector," *Energy Reports,* vol. 3, pp. 119-123, 2017.

[65] S. Madhankumar, K. Viswanathan, and W. Wu, "Energy, exergy and environmental impact analysis on the novel indirect solar dryer with fins inserted phase change material," *Renewable Energy,* vol. 176, pp. 280-294, 2021.

[66] M. Sajawal, T.-u. Rehman, H. M. Ali, U. Sajjad, A. Raza, and M. S. Bhatti, "Experimental thermal performance analysis of finned tube-phase change material based double pass solar air heater," *Case Studies in Thermal Engineering,* vol. 15, p. 100543, 2019.

[67] Ü. Ağbulut, A. E. Gürel, and Y. Biçen, "Prediction of daily global solar radiation using different machine learning algorithms: Evaluation and comparison," *Renewable and Sustainable Energy Reviews,* vol. 135, p. 110114, 2021.

[68] I. Ceylan, A. E. Gürel, H. Demircan, and B. Aksu, "Cooling of a photovoltaic module with temperature controlled solar collector," *Energy and buildings*, vol. 72, pp. 96-101, 2014.

[69] I. S. Zhelavskaya, Y. Y. Shprits, and M. Spasojevic, "Reconstruction of plasma electron density from satellite measurements via artificial neural networks," in *Machine learning techniques for space weather*: Elsevier, 2018, pp. 301-327.

[70] B. E. Boser, I. M. Guyon, and V. N. Vapnik, "A training algorithm for optimal margin classifiers," in *Proceedings of the fifth annual workshop on Computational learning theory*, 1992, pp. 144-152.

[71] G.-Q. Lin, L.-L. Li, M.-L. Tseng, H.-M. Liu, D.-D. Yuan, and R. R. Tan, "An improved moth-flame optimization algorithm for support vector machine prediction of photovoltaic power generation," *Journal of Cleaner Production,* vol. 253, p. 119966, 2020.

[72] A. Kumar, S. Ranjan, O. Prakash, and A. Shukla, "Exergy Analysis of Solar Dryers," in *Solar Drying Technology*: Springer, 2017, pp. 239-262.

[73] S. Deshi, D. Wonang, and B. Dafur, "Control of rots and spoilage of agricultural products: a review," *Academic Journal of Interdisciplinary Studies,* vol. 3, no. 7, pp. 38-38, 2014.

[74] S. Vijayan, T. Arjunan, and A. Kumar, "Fundamental concepts of drying," in *Solar Drying Technology*: Springer, 2017, pp. 3-38.

[75] J. Banout, "Solar Drying Systems," (in English), 2017.

[76] G. Pirasteh, R. Saidur, S. Rahman, and N. Rahim, "A review on development of solar drying applications," *Renewable and Sustainable Energy Reviews,* vol. 31, pp. 133-148, 2014.

[77] L. Bennamoun, "Reviewing the experience of solar drying in Algeria with presentation of the different design aspects of solar dryers," *Renewable and Sustainable Energy Reviews,* vol. 15, no. 7, pp. 3371-3379, 2011.

[78] G. Yuan, L. Hong, X. Li, L. Xu, W. Tang, and Z. Wang, "Experimental investigation of a solar dryer system for drying carpet," *Energy procedia,* vol. 70, pp. 626-633, 2015.

[79] M. Ndukwu, D. Onyenwigwe, F. Abam, A. Eke, and C. Dirioha, "Development of a low-cost wind-powered active solar dryer integrated with glycerol as thermal storage," *Renewable Energy,* 2020.

[80] S. Murali, P. Amulya, P. Alfiya, D. A. Delfiya, and M. P. Samuel, "Design and performance evaluation of solar-LPG hybrid dryer for drying of shrimps," *Renewable Energy,* vol. 147, pp. 2417-2428, 2020.

[81] H. Atalay, "Comparative assessment of solar and heat pump dryers with regards to exergy and exergoeconomic performance," *Energy,* vol. 189, p. 116180, 2019.

[82] A. Khanlari, A. Sözen, C. Şirin, A. D. Tuncer, and A. Gungor, "Performance enhancement of a greenhouse dryer: Analysis of a cost-effective alternative solar air heater," *Journal of Cleaner Production,* vol. 251, p. 119672, 2020.

[83] S. Soodmand-Moghaddam, M. Sharifi, and H. Zareiforoush, "Investigation of fuel consumption and essential oil content in drying process of lemon verbena leaves using a continuous flow dryer equipped with a solar pre-heating system," *Journal of cleaner production,* vol. 233, pp. 1133-1145, 2019.

[84] M. Cherier, T. Benouaz, S. Bekkouche, and M. Hamdani, "Some solar passive concepts in habitat through natural ventilation case study: Dry climate in Algeria Ghardaia," *Case studies in thermal engineering,* vol. 12, pp. 1-7, 2018.

[85] A. Benseddik, A. Azzi, F. Chellali, and R. Khanniche, "An analysis of meteorological parameters influencing solar drying systems in Algeria using the isopleth chart technique," *Renewable Energy,* vol. 122, pp. 173-183, 2018.

[86] A. Labed, N. Moummi, K. Aoues, and A. Benchabane, "Solar drying of henna (Lawsonia inermis) using different models of solar flat plate collectors: an experimental investigation in the region of Biskra (Algeria)," *Journal of Cleaner Production,* vol. 112, pp. 2545-2552, 2016.

[87] S. Boughali, H. Benmoussa, B. Bouchekima, D. Mennouche, H. Bouguettaia, and D. Bechki, "Crop drying by indirect active hybrid solar–Electrical dryer in the eastern Algerian Septentrional Sahara," *Solar energy,* vol. 83, no. 12, pp. 2223-2232, 2009.