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Experimental Study of a New Design of a Solar Dryer Assisted by Photovoltaic Cell

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Experimental Study of a New Design of a Solar Dryer Assisted by Photovoltaic Cell

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DEDICATION

To those who gave me everything without anything in return to those who have encouraged and supported me in the most difficult times and those to whom I owe so much

To my dear parents for their love, support and patience. I thank them especially since I thank no one

I hope that one day my good God will give me the opportunity to honor them and give back what they deserve.

To our three dear brothers and sisters.

To all our families (Kourrak, Abdellaoui, Lilah).

To all our teachers.

To all our friends.

HADDA

DEDICATION

To my cherished family, supportive friends, and dedicated teachers,

As I stand on the threshold of this achievement, I'm reminded of the incredible network of love and encouragement that surrounds me. To my family, including my beloved late grandfather (رحمه الله), your unwavering belief in my potential has been my driving force. (the "Rehimat and Khamed" family).

To my friends, your laughter, camaraderie, and shared experiences have enriched my journey in unimaginable ways.

To my teachers, your guidance and dedication have ignited my passion for learning and growth.

This milestone isn't just about me—it's a testament to the collective support of all of you.With heartfelt appreciation.

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Abstract

This master's thesis presents an experimental investigation into the drying characteristics, kinetics modeling, and performance assessment of an innovative direct forced convection solar dryer integrated with photovoltaic power. The solar dryer was meticulously crafted within the confines of the Applied Research Unit in Renewable Energy, utilizing cost-effective materials, and synergized with a 10-watt photovoltaic panel. Operational conditions of the dryer are regulated by a sophisticated control system, synchronized with real-time meteorological data via an Arduino interface.

The study conducts drying experiments on fresh mint, parsley, and henna samples. The objective is to reduce their initial moisture content from 83.55 % (w.b) for mint, 79.1 % (w.b) for parsley, and 65.84 % (w.b) for henna to the respective target moisture levels of 7.22 %, 6.48 %, and 3.73 % (w.b) within specific timeframes of 7h:34min for mint, 8h:40min for parsley, and 6h:28min for henna. Mathematical modeling of the drying process is performed, revealing that the Midilli-Kucuk model adeptly predicts the drying behavior of fresh mint, parsley, and henna samples.

Furthermore, the control system, which dynamically adjusts drying temperatures based on real-time weather data, is rigorously tested and proven to be highly effective.

This work contributes valuable insights into the practical implementation of solar drying systems powered by photovoltaic cells, offering a sustainable and energy-efficient solution for preserving agricultural produce. The findings underscore the feasibility and efficiency of such integrated systems, paving the way for broader adoption in renewable energy-driven agricultural processes.

KEY WORDS: Control solar dryer; Photovoltaic-assisted dryer; Empirical model; Drying kinetics; mint drying; Parsley drying; Henna drying; Experimental study; Moisture content reduction.

Résumé

Ce mémoire de Master présente une enquête expérimentale sur les caractéristiques de séchage, la modélisation de la cinétique et l'évaluation des performances d'un innovant séchoir solaire à convection forcée direct assisté par cellule photovoltaïque. Le séchoir solaire a été méticuleusement conçu au sein de l'Unité de Recherche Appliquée en Énergies Renouvelables, en utilisant des matériaux économiques et en étant associé à un panneau photovoltaïque de10 watts. Les conditions opérationnelles du séchoir sont régulées par un système de contrôle sophistiqué, synchronisé avec des données météorologiques en temps réel via une interface Arduino. L'étude mène des expériences de séchage sur des échantillons de menthe fraîche, de persil et de henné. L'objectif est de réduire leur teneur en humidité initiale de 83,55 % (w.b) pour la menthe, 79,1 % (w.b) pour le persil et 65,84 % (w.b) pour le henné aux niveaux d'humidité cibles respectifs de 7,22 %, 6,48 % et 3,73 %. (w.b) dans des délais précis de 7h:34min pour la menthe, 8h:40min pour le persil et 6h:28min pour le henné. Une modélisation mathématique du processus de séchage est réalisée, révélant que le modèle Midilli-Kucuk prédit de manière compétente le comportement de séchage des échantillons de menthe fraîche, de persil et de henné. De plus, le système de contrôle, qui ajuste dynamiquement les températures de séchage en fonction des données météorologiques en temps réel, est rigoureusement testé etprouvé comme étant très efficace. Ce travail apporte des informations précieuses sur la mise en œuvre pratique de systèmes de séchage solaire alimentés par des cellules photovoltaïques, offrant une solution durable et économe en énergie pour la préservation des produits agricoles. Les résultats soulignent la faisabilité et l'efficacité de ces systèmes intégrés, ouvrant la voie à une adoption plus large dans les processus agricoles pilotés par l'énergie renouvelable.

Mots clès :Control solar dryer; Photovoltaic-assisted dryer; Empirical model; Drying kinetics; mint drying; Parsley drying; Henna drying; Experimental study; Moisture content reduction.

ملخص

تقدم مذكرة الماستر هذه تحقيقًا تجريبيًا في خصائص التجفيف ونمذجة الحركية وتقييم األداء لجهاز شمسي بتكثيف قوة الهواء المباشر المبتكر مدمج مع طاقة الخاليا الشمسية. تم تصنيع الجهاز بعناية داخل وحدة البحث التطبيقي في مجال الطاقة المتجددة باستخدام مواد مكلفة بشكل فعّال ومتكامل مع لوحة خاليا شمسية بقوة 10 واط. تتم تنظيم الظروف التشغيلية للجهاز من خالل نظام تحكم متطور متزامن مع بيانات الطقس في الوقت الحقيقي عبر واجهة Arduino.

أجرت الدراسة تجارب تجفيف على عينات من النعناع والبقدونس والحناء الطازجة. الهدف هو تقليل محتوى الرطوبة األولي من 83.55%)وزن(للنعناع، و79.1%)وزن(للبقدونس، و65.84%)وزن(للحناء إلى مستويات الرطوبة المستهدفة البالغة 7.22%، و6.48%، و3.73%)b.w(ضمن أطر زمنية محددة هي 7 ساعات: 34 دقيقة للنعناع، و 8 ساعات: 40 دقيقة للبقدونس، و 6 ساعات: 28 دقيقة للحناء.

تم إجراء النمذجة الرياضية لعملية التجفيف، مما يكشف أن النموذج(Kucuk–Midilli(يتنبأ ببراعة بسلوك التجفيف لعينات النعناع والبقدونس والحناء الطازجة.
عالوة على ذلك، فإن نظام التحكم، الذي يقوم بضبط درجات حرارة التجفيف ديناميكيًا بناً ء على بيانات الطقس في الوقت الفعلي، تم ا ختباره بدقة وثبت فعاليته العالية .

يساهم هذا العمل برؤى قيمة في التنفيذ العملي ألنظمة التجفيف بالطاقة الشمسية التي تعمل بالخاليا الكهروضوئية، مما يوفر حالً مستداً ما وموف ًرا للطاقة للحفاظ على المنتجات الزراعية. وتؤكد النتائج جدوى وكفاءة مثل هذه األنظمة المتكاملة، مما يمهد الطريق العتمادها على نطاق أوسع في العمليات الزراعية التي تعتمد على الطاقة المتجددة.

كلمات مفتاحية : التحكم في المجفف الشمسي؛ مجفف بمساعدة الخلايا الكهروضوئية. نموذج تجريبي؛ حركية التجفيف؛ تجفيف النعناع تجفيف البقدونس تجفيف الحناء؛ دراسة تجريبية؛ تقليل محتوى الرطوبة.

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ABBREVIATIONS

Symbols	Designations	Units
V	Air velocity	m/s
S	Standards errors values	-
T	Temperature	°C
Θ	Temperature	°C
X	Moisture content	kg water/kg dry matter
T	Time	h
X_{eq}	Equilibrium moisture content	kg water/kg dry matter
X_m	Monolayer moisture content	kg water/kg dry matter
m_o	Initial wet mass of the product	Kg
md	the dry mass of the product	Kg
m_w	Wet mass	Kg
md	dry mass	Kg
XR	Moisture ratio	-
X_0	Initial moisture content	kg water/kg dry matter
m_w (t)	The wet mass values of the product must be recorded at different times	Kg

X(t)	Moisture content at the moment t of drying	kg water/kg dry matter
Y	Mass of water vapor at θºC	Kg
Cpa	Massive heat of air	$J.kg^{-1}.C^{-1}$
Cpe	Mass heat of water	$J.kg^{-1}.C^{-1}$
H	The enthalpy of moist air	$J.kg^{-1}$
db	Dry-based water content	-
Wb	Moisture-based water content	-
Lv	The latent heat of vaporization of water at 0ºC.	$J.kg^{-1}$
Ω	Absolute humidity	kg water/kg dry matter
pH	Potential hydrogen	-
P	Indicates the total air pressure	Pa
$Pvap$	The partial pressure of water vapor	Pa
HR	Relative humidity	%
ΔE	Color distance	-
Ps	Pressure of water vapor	Pa
Ts	Surface temperature	°C
Aw	Water activity	-
Psat	Saturation pressure	Pa
ΔX	The water content difference	kg water/kg dry matter
Δt	The time difference	h
exp	Exponential function	-
Ln	Logarithm napery	-
PV	Photovoltaic	-
MR	Reduced water content	Kg of water/Kg of dry matter
MR0	Initial water content	Kg of water/Kg of dry matte

GENERAL INTRODUCTION

GENERAL INTRODUCTION

Algeria is a country blessed with abundant sunshine, making it an ideal location for solar drying. With an average annual sunshine duration of around 2,500 hours and daily average solar energy of 16.2 to 27 MJ/m² on the horizontal plane, the country has the potential to satisfy all the energy demand for drying agricultural products **(A.Boussalia)**. Solar drying has been widely used to preserve food and is considered the most common application of solar energy. Drying fruits, vegetables, and meats is an energy-intensive process in the food processing industry, and solar drying offers a better way to reduce post-harvest expenses and losses. While traditional drying methods involve direct exposure to sunlight, it suffers from several limitations, such as an inability to control the drying process, uncertainty in drying time, high labor costs, and insect and foreign body contamination. To overcome these challenges, solar dryers have been proposed, which can efficiently dry agricultural products while improving the quality of the final product. Many studies have been conducted on solar drying, including modeling of agricultural products and simulation studies on solar dryers, such as direct and indirect solar dryers. Such studies focus on the drying kinetics of different vegetables and fruits. By introducing solar dryersin developing countries, crop losses can be reduced, and the quality of dry products can be significantly improved compared to traditional drying methods. Designing a solar dryer requires considering specific crop requirements, drying characteristics of the materials, and simulation models for natural convection and forced drying systems. Properly designed solar dryers can alleviate the challenges associated with traditional drying methods while reducing the cost of labor and providing non-polluting, renewable energy.

Present research work involves an innovative design and construct a solar dryer that can efficiently dry herbs using renewable energy while also ensuring consistent and high-quality results. The solar dryer will be constructed using low-cost construction materials. An Arduino microcontroller will be utilized to control the drying temperature and fan speed, with temperature and humidity sensors included to monitor the drying process. By testing the system with various herbs, we can determine the optimal drying parameters and contribute to the development of sustainable agriculture practices while encouraging the use of renewable energy sources.

Research Goal:

- To develop a sustainable and efficient method for solar drying herbs using renewable energy sources.

Research Objectives:

- ✓ To design and construct a solar dryer that can effectively dry herbs using renewable energy sources.
- ✓ To determine the optimal temperature and humidity conditions for drying different types of herbs using the solar dryer.
- ✓ To evaluate the efficiency and effectiveness of the solar dryer in comparison to traditional drying methods.
- ✓ To assess the economic and environmental impacts of using a solar dryer for herb drying.

By achieving these research objectives, this project can potentially contribute to the development of sustainable and efficient methods for herb drying, and encourage the use of renewable energy sources in agriculture.

In the first chapter of this thesis, we will delve into the fundamental concepts related to the drying process. This will encompass its definition, objectives, and underlying principles. Additionally, we will explore various drying techniques employed in the industry, providing an overview of each method.

Moving on to the second chapter, we will conduct a comprehensive literature review on our chosen subject. We will review relevant research and previous studies, summarizing key ideas and significant findings in this context.

In the third chapter, we will discuss the practical applications conducted within the scope of this thesis. We will present details of the research and experiments carried out, elucidating the methodology employed. Furthermore, we will highlight the main results obtained from these experiments.

In the final chapter, we will offer our conclusions and evaluate the results based on the content presented in the preceding chapters. We will provide an overview of the primary contributions of this thesis and also address limitations and future recommendations for research in this field.

Chapter I

General drying notion

I.1. Introduction

Solar drying is a food preservation method that uses the energy from sunlight to dry fruits, vegetables, grains, and other food products. The process involves exposing the food to direct sunlight and circulating air to remove moisture and reduce water content, which helps prevent spoilage and extend the shelf life of the food. Sun drying is a low cost and environmentally friendly technology that has been used for thousands of years in various parts of the world, particularly in areas with high solar radiation and low humidity. In addition to preserving food, sun drying can also help improve the nutritional value of some crops, such as fruits and vegetables, by reducing their moisture content and concentrating their nutrients. Overall, sun drying can be a great alternative to traditional drying methods, which often require large amounts of energy and can be costly and environmentally damaging.

I.2. Drying technology

Drying technology is a process of removing moisture or water from a material. There are various types of drying technologies available, including convection drying, freeze drying, spray drying, vacuum drying, microwave drying, and infrared drying. Convection drying uses hot air to remove moisture, while freeze drying involves freezing the material and then removing the ice through sublimation. Spray drying produces a dry powder from a liquid or slurry by rapidly drying with hot gas. Vacuum drying reduces the pressure to lower the boiling point of water and accelerate the drying process. Microwave and infrared drying use electromagnetic radiation to remove moisture from materials. The choice of drying technology depends on the material being dried, the desired end product quality, and the specific needs of the industry.

I.3. Definition of drying

Drying is the process of removing moisture or water content from a material, substance, or object. It involves exposing the material or object to heat, air, or other means ofremoving moisture to reduce the water content to a level that is acceptable for its intended use. Drying is commonly used in various industries such as food processing, agriculture, and manufacturing to preserve, store, or prepare materials or products for further use.

I.4. Application areas of drying

Much of the food we consume has undergone a drying operation. Drying can be a necessary step in the production of the product or a role in the preservation of the food. Wecan quote for example:

- food products.
- The charcuterie: sausage, jambon...
- Cheese: drying in a controlled atmosphere.
- Vegetables (weed ,...) and dried fruits (pearls, grapes, apricots...).
- Some aperitive biscuits are produced by drying in hot air from a corn patch.
- Salt is crushed, dissolved, purified before being sprinkled and finally dried until it becomes refined.
- The preservation of many types of grains or plants is ensured by drying: coffee, cocoa, rice and other cereals, tea leaves, spices...
- Certain products: milk, serum etc.
- Co-products of the food industry often intended for the feeding of livestock, or the chemical industry (additives...): beet pulp (sweets), turtles of oleagins (oilers), trees (breweries, apple juice) ... **(Benseddik, 2011).**

I.5. Purpose of drying

Drying is a process that involves the removal of moisture or water from a substance or material. The purpose of drying can vary depending on the specific application or industry, but some common reasons for drying include:

- **Preservation:** Drying can be used to preserve food, herbs, and other perishable items by removing the moisture that can promote the growth of bacteria, mold, and other microorganisms.

- **Improving shelf life:** Many products, such as pharmaceuticals, chemicals, and textiles, can benefit from drying to improve their shelf life by reducing the risk of spoilage or degradation over time.

- **Processing:** Drying is often a necessary step in processing materials such as wood, paper, and metal. By removing moisture, the materials can be shaped, cut, and treated more effectively.

- **Energy efficiency:** Drying can help reduce the energy needed to transport and store materials by reducing their weight and volume.

- **Enhanced quality:** Drying can also be used to enhance the quality of some products, such as coffee, tea, and tobacco, by removing excess moisture and improving flavor, aroma, and texture.

I.6. Mechanism of drying

A representation of the transport phenomena occurring during the thermal drying of a solid food material is illustrated in the **(figure 1).** In convective food material drying, two separate transport mechanisms occur simultaneously, involving heat transfer from the drying area to the food material and water transport (in liquid or steam form) from the inside of the solid product toits surface and eventually to the air by evaporation. **(Sablani and Rahman, 2007)**

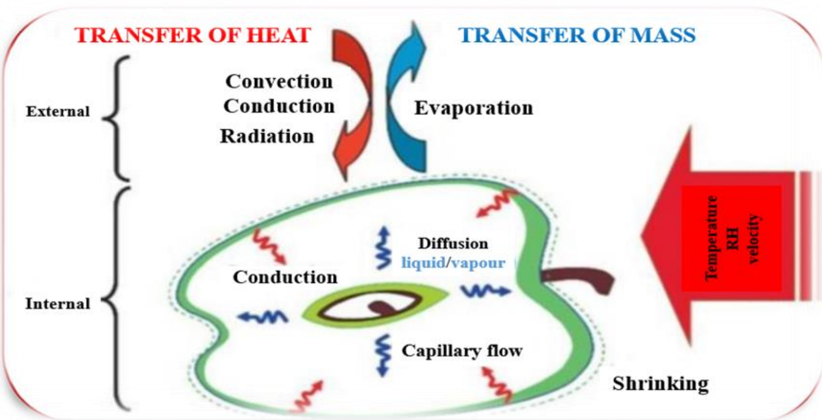

Figure I. 1: Thoretical representation of the heat drying process of a solid food material (Sabarez, 2018)

I.6.1. Transfer of heat

- **By Driving:**

The product to be dried is in contact with a solid wall brought to a temperature high by heating (smoke, water vapors...). Conducting Through Walls and Matter This results in an increase in the temperature of the compound to be dried: the liquid then vaporizes. by evaporation or by boiling if it reaches its boiling temperature. **(Chouicha. 2010)**

- **By convection:**

This is the most widely used drying method in the chemical industry, thermal exchange is It is achieved through direct contact between the wet solid and the heat carrier gas. **(Chouicha. 2010)**

- **From the radiation**

Radiant energy techniques (Ultra Violet, Infrared, High Frequency, Microwave) ensure, when the product allows, a very good quality drying and significantly reduce the costsassociated with the power station. **(Chouicha. 2010)**

I.6.2. Transfer of mass

Mass transfer plays a very important role in basic unit operations, such as drying. In these physical operations, resistance to mass transfer is the limiting factor, although heat transfer and fluid flow are involved in packaging and storage where the transfer of moisture, vapors, gases and aromatic compounds, influence the quality of the food. **(Saravacos, 1995).**

The difficulties of applying mass transfer theories, in food processing processes, result from complex physical structures and the chemical composition of food products that vary for the same commodity and change during processing. **(Saravacos, 1995).** It should be noted that the migration of water (liquid or steam) can also be carried out by “filtration” through the porous product under the action of a pressure difference between the interior and the surface. **(Bimbenet, 1984).**

I.7. Descriptive theories of the phenomenon of drying

I.7.1. The diffusion theory

The passage describes the Fick law, which explains the migration of water vapor from areas of high concentration to low concentration, and how it can be used to explain the drying of foods and grains. However, the Fick law has limitations in representing physical phenomena, as it only considers the difference in concentration and ignores factors like internal temperature gradient or diffusion coefficient. The diffusivity of water in food productsat 50 degrees Celsius is also provided, and it varies depending on factors such as the nature of the solid and the humidity and temperature **(Charrreau and Cavaille, 1991), (Bimbenet,1984).**

I.7.2. Whitaker's Theory

It is the most recent theory, which exhibits excellent agreement with experimental results. It is based on the continuity equation, the quantity of motion equation, the energy equation for the three phases of the matter, and the thermodynamic laws. **(Whitaker, 1980).**

I.7.3. Luikov's Theory (1934)

Luikov discovers the phenomenon of thermal diffusion of humidity (the temperature gradient is one of the factors causing moisture transfer). **(Bennamoun, 2001).**

I.7.4. The Capillary Theory (1937)

The passage discusses the capillary theory, which explains the movement of water through porous or granular products. The theory is based on the suction potential created by the molecular attraction between the liquid and solid surfaces. The rise of liquid in a capillary tube placed in a tank of water is used to illustrate this concept. Capillarity is responsible for the upward flow of liquid through the interstices of a product during drying. The first period of drying is controlled by capillarity, according to Krischer's research, which was supported by Gorling's experiment on potatoes. Other theories have been developed based on the capillary theory. **(Charrreau and Cavaille, 1991)**

I.7.5. The Krischer-Berger and Pei theory (1938)

The first postulates that during drying, moisture in the liquid and vapor states is caused by capillary forces and vapor concentration gradients, respectively. The final two suggest that the transfer of liquid is caused by capillary forces and a gradient of concentration. Vapor diffusion is caused by a gradient of vapor pressure. **(Bennamoun, 2001).**

I.7.6. Theory of Philip and De Vries (1957)

Philip and De Vries, suggest that the movement of water is due to the capillarity and diffusion of steam. This theory is based on the development of a system of equations describing moisture and heat transfer in porous materials. **(Mihoubi, 2004).**

I.8. Main agents of the convection drying operation

I.8.1. The product to be dried

The beginning mass m0 and initial water content X0 of the product to be dried are experimentally determined characteristics. The wet mass values of the product md (t) must be recorded at various intervals ti in order to track the drying process. Once the measured dry mass is known, the water content as a function of time can be calculated on either a wet or dry basis.

The amount of water in a product expressed as a percentage of its wet mass is known as moisture-based water content (wb) or water content (Mennouche, D. 2006).

$$X(t)\ \frac{mw(t) - md}{mw(t)} \qquad (1)$$

Dry-based water content (db) or moisture content [Mennouche. D, (2006)]: it is themass of watercontained in the product in relation to its dry mass.

$$\mathrm{X(T)} = \frac{mw(t) - md}{md} \qquad (2)$$

Or: m_d: is the measured dry mass of the product, it is preserved during the drying operation and is calculated by the following formula:

$$md = m0/(1 + x0) \tag{3}$$

Or: m0 is the initial wet mass of the product.

I.8.2. Wet air Enthalpy of moist air

The enthalpy of moist air defines the energy content of this air. The enthalpy noted H of 1 kg of dry air combined with Y kg of water vapor at θºC represents the amount of heat to be supplied to this mixture under a constant pressure for bring it from the reference temperature 0ºC to the temperature of θ°C. The reference states to consider are liquid water and dry gas at 0ºC. The enthalpy of moist air H is the sum of the enthalpy of air and the enthalpy of water.

$$H = Cpa\theta + Y\,(Lv + Cpe\theta) \tag{4}$$

Or: Cp_a and Cp_e are respectively the mass heats of air and water in the gaseous state and L_v is the latent heat of vaporization of water at 0ºC.

I.8.3. Temperature and humidity

The partial pressure of water vapor P_{vap} in the atmosphere is never zero whatever the place and the season, although its value can vary greatly.

I.8.4. Absolute humidity ω

It is defined for moist air (or other gases) as its moisture content. It is limited by the maximum quantity that the gas can absorb before saturation at the temperature of it.

$$\omega = 0.622\frac{\mathrm{Pvap}}{p - Pvap} \rightarrow \mathrm{Pvap} = \frac{\omega}{0.622 + \omega}p \tag{5}$$

Where P: indicates the total air pressure**.**

I.8.5. Relative humidity (or degree of hygrometry)

Corresponds to the ratio of the partial pressure of water vapor contained in the air to the saturation vapor pressure (or vapor pressure), at the same temperature and pressure.It is therefore a measure of the ratio between the water vapor content of the air and its maximum capacity to contain it under these conditions. This ratio will change if the temperature or pressureis changed even though the absolute humidity of the air has not changed. Relative humidity is measured using a hygrometer. It is expressed most often in percentage and its expression becomes:

$$\text{Humidity Relative (HR)} = \text{pvap}/(\text{Psat}(\text{T})) \times 100\% \qquad (6)$$

I.8.6. Relation between relative humidity, absolute humidity and temperature

Absolute humidity is defined as the total mass of water vapor in a given volume. It is not dependent on temperature. There is an inverse relationship of relative humidity with temperature. This means on increasing temperature, relative humidity decreases. (Jean Cstang, 2003).

$$\text{HR} = \text{p}/(\text{Psat}(\text{T})) \times \omega/(0.622 + \omega) \times 100 \qquad (7)$$

I.8.7. Expressions of calculation of Psat

The approximate calculation of the saturation vapor pressure Psat can be done usingseveral formulas available in the literature such as:

- Dupré formula:**(**Yves Jannot 2005,**)** valid between-50°C and + 200°C to calculate P_{sat} (T):

$$\text{Psat}(\text{T}) = \exp[46.784 - 6435/(\text{T} + 273.15) - 3.868 \ln(\text{T} + 273.15)] \qquad (8)$$

Or:

T: Temperature in (°C).

$P_{sat}(T)$: saturation pressure in (mmHg).

- Rankine formula [Free Encyclopedia]: it takes the previous one with slightly different coefficients (deviation of 0.39 to 4.1% over the range of 5 to 140°C compared to the thermodynamic tables):

$$\mathrm{Ln(Psat)} = 13.7 - 5120/\mathrm{T} \qquad (9)$$

With:

Psat: saturation vapor pressure of water,

T: absolute temperature, in (K). in (atm).

I.8.8. Water activity in food

The a_w water activity is a classic quantity used to evaluate the ability of a product in a given atmosphere to degrade from a biological point of view. It corresponds to the ratio between the pressure of the water vapor of the food (pressure of the water vapor at the surface of the product) and the pressure of the pure water vapor at the same temperature θ_0.

$$\mathrm{Law} = \frac{(\text{partial pressure of the water vapor of the food at}\varnothing)}{(\text{partial pressure of pure water at }\theta)} \qquad (10)$$

The activity of water in a product also represents the relative humidity of an air in equilibrium with the product (when there is no more exchange of water between them). The value of the water activity varies between zero (dry product to the point that all the wateris linked to the food, and the reform without reactive quality) and 1 (pure water without solute,difficult to reach and above all to maintain).

The optimum value for the conservation of biological products, without additives or refrigeration, corresponds to a water activity of between 0.25 and 0.35; the growth of bacteria is generally limited when the water activity drops below 0.90 and the molds and yeasts are respectively inhibited to an activity of 0.70 and 0.80 **(**Jean-Jacques Bimbenet. 2002.Food Process Engineering RIA Dunod edition, Paris).

I.9. Drying Kinetics

Due to the simultaneous effects of multiple elements, the drying mechanisms are complicated. These variables include the drying method and the product's attributes (nature, form, and physical features). These factors make it impossible to establish a single model that can adequately capture the drying kinetics in all circumstances. Drying rate Vs = -dX/dt (kg of water per kg of dry matter per unit of time) is the average of the ratio of the water content differential X by the time interval t. The size essentially determines the transfer's speed. (Benaouda . 2006).

The drying speed is a function of many parameters, the most important of which are:

- The nature, porosity, shape and moisture of the product.
- The temperature, humidity and speed of the dryer gas.

I.10. Different phases of a convective drying

The drying kinetics of the various products are studied by curves representing the evolution of the drying rate as a function of time. These curves are generally obtained for different experimental conditions (temperature, hygrometry, air velocity, etc). They characterize the overall behavior of the product to be dried over time. All the drying work shows that the securves are distinguished according to the nature of the product. In general, there are three different periods that are characterized by a different behavior of the drying speed: if, in a drying operation, the mass of the intervals, the so-called curve of the drying speed will be obtained. On this curve **figure** (I.2) we distinguish three regions explainedas follows:

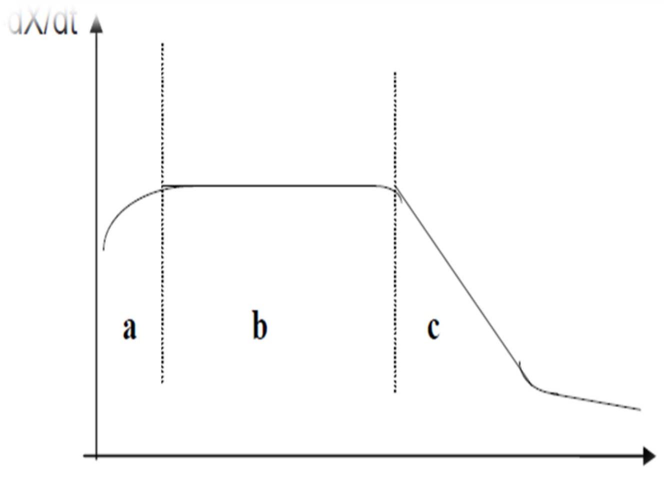

Figure I. 2: Drying rate as a function of time. (Touati **2001).**

This is the warm-up period. When a product of a surface temperature Ts and a partial pressure of water vapor Ps are stirred by a stream of hot air, exchanges of heat and material take place between the product and the drying air. To be carried as a vapor, the quantities of water contained in the product require a corresponding input of the vaporization energy. The excess heat provided by the air causes the product to heat up further resulting in a balance of the heat balance. If, on the other hand, the surface temperature of the product is too high, the energy deficit would lead to a cooling of the product. The warm-up period is short and really only appears if the products are large, or if the temperature difference betweenthe air and the product is important. **(Benaouda, 2006).**

- ✓ **Region b**

It is the period with a constant speed of drying; it exists only if the free water evaporates on the surface. The activity of the water on the surface of the product is then equal to one and the drying is called isenthalpic. For this period, it is possible to define the temperature of the wet thermometer. This is the temperature at which the inflow of heat entering is equal to the flow necessary for the evaporation of the water leaving the product.

- ✓ **Region c (Downturn period)**

This is the period with decreasing drying speed. The slowing down of the drying rate is explained by the following phenomenon: Disappearance of free water in the product surface: this phenomenon corresponds to the beginning of the slowdown of the drying rate. Assuming that the migration of the free water and the bound wate contained in the product takes place consecutively in liquid and vapor form, it is necessary to envisage the existence of a vaporization front which progressively sinks to the inside the product.

I.11. Parameters influencing the kinetics of drying

- Temperature of drying air (Ta).
- Relative Humidity of Air (Hr).
- The speed of drying air (Va).
- Recycling rate of drying air.
- The caliber of the product to dry.
- Thickness of the product to dry (Ep).

I.11.1. Influence of the drying air temperature (Ta):

The drying speed is substantially impacted by the drying air temperature. This effect is brought on by the product's receiving heat from the air temperature. She is also a result of the product's temperature, which is even more crucial than the temperature It's up in the air. Thus, the rate of water diffusion in the product becomes crucial. **(Mennouche.2006).**

I.11.2. Influence of drying air humidity (Hr):

The water content of the air has a significant impact on how air moves and behaves. Some products appear to be more affected by this influence at the beginning of the drying process than at the end. diminishing and drying when air temperature rises. **(Mennouche.2006).**

I.11.3. Influence of the drying air speed (Va):

The air speed has a favorable impact on drying kinetics, especially early in the process. For goods, however, whose drying kinetics is governed by migration. When internal water is present, the impact of air drying speed is quite minimal. **(Mennouche.2006).**

I.11.4. Influence of the drying air speed (Va):

The air speed has a positive effect on the drying kinetics especially at the beginning of the operation. However, for products whose drying kinetics is controlled by migration. **(Kouhila ; Belghit ; Boutaleb, 2000).**

I.11.5. The caliber of the product to be dried:

The rate of dehydration also depends on the rate of intracellular diffusion. The dilution water of the cell juice; function itself of the thickness of the fruit. Drying behavior depends on their morphological characteristics. In fact, the date is used entirely to get closer to the actual conditions of the dates (Matallah.2004).

I.11.6. Influence of the thickness of the product to dry (Ep)

If this thickness is increasing, it means that the water vapor must. This is a long journey that explains, and largely, this slowdown. The appearance of drying. **(Mennouche.2006).**

I.12. Drying systems

Systems for solar drying are often categorized based on how they are used. Using solar energy for heating. They can generally be divided into two main groups, namely:

- Hybrids and active solar energy drying devices (sometimes referred to as sun dryers).
- Drying air circulates naturally in passive solar energy devices, also referred to as solar dryers.

There are three different subclasses for these two active and passive drying methods(depending on the type of dryer and how the energy is used). The solar system is made up of:

- Direct type solar dryers.
- Indirect type solar dryers.
- Mixed mode solar dryers.
- Hybrid solar drying.

I.13. The main types of solar dryers

I.13.1 Direct type solar drying

Direct-type solar drying is a technique for drying agricultural products by exposing them to direct sunlight. This process involves placing the product on a flat surface, typically a tray or a mesh screen, where it absorbs the sun's energy and evaporates moisture into the surrounding air. The air is heated by the sun and rises, creating a natural convection that draws in cooler air from below, further facilitating the drying process. Direct-type solar drying is a cost-effective and environmentally friendly way to preserve perishable agricultural products.

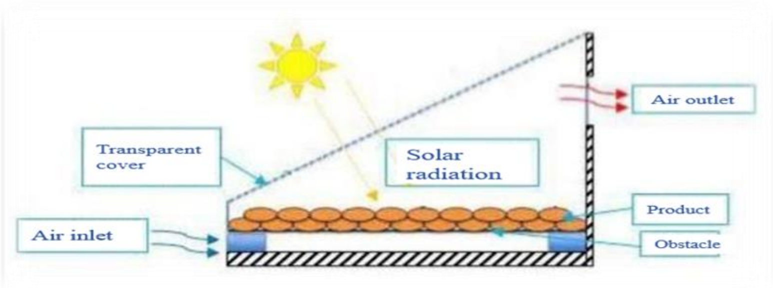

Figure I. 2: Drying rate as a function of time. (Touati 2001).

Table I. 1: Advantages and disadvantages of a direct solar dryer

advantages	disadvantages
• Compared to conventional drying, this provides better protection against dust, insects, animals, and rain. • No skilled workforce required.	• Near the conclusion of drying, a high temperature. • The oxidation of vitamins A and C caused by solar exposure. • Insufficient airflow slows drying and raises the danger of mold.

I.13.2. Indirect type solar drying

In indirect solar dryers, drying products are not directly exposed to sunlight. They are even protected from light leading to better preservation of the nutritional qualities of the food. Indirect dryers consist mainly of two parts: a solar sensor and a drying chamber. A solar sensor is usually a separate module that is attached to the drying chamber during exposure to the sun and whose inclination is intended to maximize the capture of solar energy. It consists of a glass surface located above and an absorbent surface, usually painted in black. The air is first heated in the solar sensor, then conducted into the drying chamber where a heat transfer from the air to the product and a mass transfer of the product to the air occur during the course of drying air. (**Souheyla., 2018).**

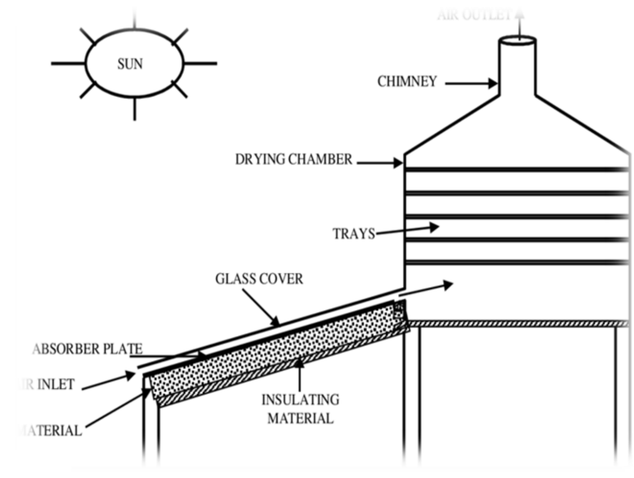

Figure I. 4: The principle of an indirect solar **dryer.**

Table I. 2: Advantages and disadvantages of a indirect solar dryer:

Advantages	disadvantages
• Direct sunshine is not shining on the product. The color and nutritional value, particularly the vitamins A and C, are better preserved. • The ability to construct locally and affordably this type of dryer. • Neither fossil fuels nor electricity are needed for their operation.	• Extremely variable drying speed based on dryer design and environmental factors. • Polyethylene materials are brittle and need to be replaced frequently.

I.13.3. Mixed-mode drying

These dryers integrate the principles of both direct and indirect drying methods. The products experience a dual effect, as they are exposed to direct solar radiation while also being subjected to heated air through a sensor positioned beneath the drying chamber. In mixed solar dryers, both the upper surfaces of the drying chamber and the sensor are typically covered with glass or transparent films to facilitate these processes. **(Amar, 2010).**

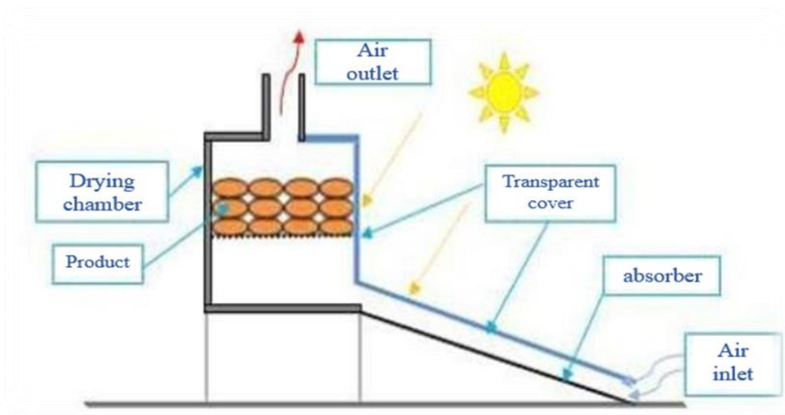

Figure I. 3: Principle of a mixed solar dryer **[Souheyla.,2018].**

I.13.4. Hybrid solar drying:

These dryers use, in addition to solar energy, additional energy (fuel, 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 usually reserved for large-scale applications, or applications commercial in which the quality and flow of the final product may depend on climatic conditions. The most widely used drying methods in industry are:

- Hot air drying or 'traditional' drying.
- Overheated steam drying.
- Heat pump drying.
- Drying by hot chamber.
- Vacuum drying.

The last two drying processes are mainly used for drying wood. (Touati., 2017).

Table I. 3: Advantages and disadvantages of a Hybrid solar drying

Advantages	disadvantages
• Freezing from climate conditions. • Improved drying control.	• Extremely variable drying speed based on dryer design and environmental factors. • Polyethylene materials are brittle and need to be replaced frequently.

I.14. Types of changes in the quality of the dry product

I.14.1. Biochemical changes due to temperature:

Exposure to an organic product for a given period its chemical makeup may change as a result of high drying. Ces There are several modifications, most of which are viewed as bad. Yet the most. The following points are crucial:

- Maillard reactions are non-enzymatic processes that happen when proteins and carbohydrates are combined. Together with this reaction, the other response nutrition loss.
- Fat oxidation (rancissement).
- Vitamin eradication.
- Denaturation of proteins, decreasing their ability to rehydrate when using produce and alter their power liant or moussant.
- Enzymatic reactions: If the enzymes are still active after being exposed to heat during drying, they will cause consequences like the browning of polyphenols and the hydrolysis of lipids, among others.

I.14.2. Loss of Aromas:

Drying is a volatility-based separation process. The water in it had. The item won't be thrown away on its own. Yet, it is present in every other volatile product as well. These are often the aromas found in the. For use in food, organic products.

I.14.3. Physical and mechanical changes:

Drying causes physical and mechanical damage to most plants. Characterized by:

- Migration of solvents to the surface: In addition to affecting how the product looks, this buildup of sugars or other solids on the surface reduces the value of the products that are ingested when hydrated.
- Fat fusion and fat migration.
- Shape changes: Typically, the removal of water from the product causes a thing falls over on itself. When a solid matrix is present and the water starts moving

quickly, it is sometimes possible to create a product. Similar in size but with a substantial structure.

I.15. Conclusion

The first chapter gave us an overview of solar drying as one of the major applications of renewable energy. It relies on various methods, techniques and tools to success this process optimally. Solar drying is mainly based on the use of specific methods and materials based on needs, aimed at achieving its objectives and ensuring effective drying.

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Chapter II

Literature Review

II.1. Introduction

This literature review provides a comprehensive analysis of 35 research papers published between 1995 and 2022 on solar dryers. It covers various aspects of solar dryer technology, with a primary focus on the performance characteristics of solar dryers, including drying efficiency, drying rate, and product quality. The review also examines different components of solar dryers, such as the solar collector, absorber, heat exchanger, and drying chamber. Additionally, it highlights the utilization of a fan connected to the solar panel as a fundamental component for air circulation and temperature control.

While the primary application of solar dryers lies in the agricultural and food industries, most of the research is centered around these domains. However, the potential use of solar dryers in other applications, such as timber drying, textile drying, and drying of medicinal plants, has also been explored in some research papers. The cost of solar dryers has been a significant concern, prompting several research papers to explore methods for reducing the initial investment and enhancing the cost-effectiveness of solar dryers. This literature review suggests that solar dryers have significant potential as a sustainable and cost-effective solution to meet various drying needs.The proposed literature review is explaine below.

P. Schirmer et al. (1995), conducted an experiment of a solar tunnel dryer for drying bananas in Thailand. The dryer was designed to dry up to 300 kg of ripe bananas in 3-5 days, resulting in high quality. Using three fans powered by a 53W solar cell module, making it suitable for rural areas where there is no supply of electricity from the grid.

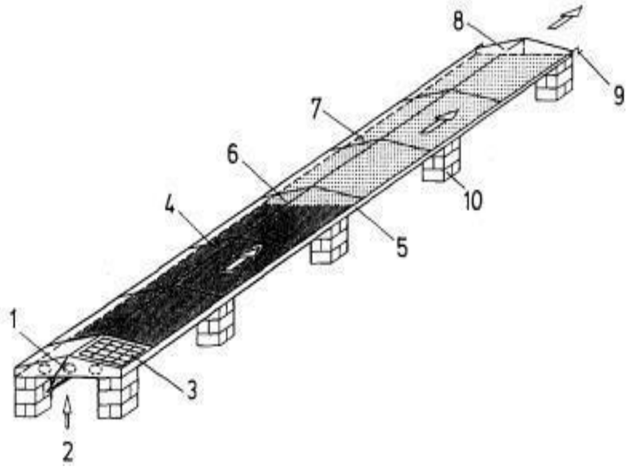

Figure II. 1: Solar tunnel dryer : (1)fan,(2)intel air,(3)solar cell module,(4) solar collector,(5)metal frame,(6)outlet of the collector, (7)drying tunnel,(8)outlet of drying tunnel,(9)rollingbar, (10)concrete block substructure.

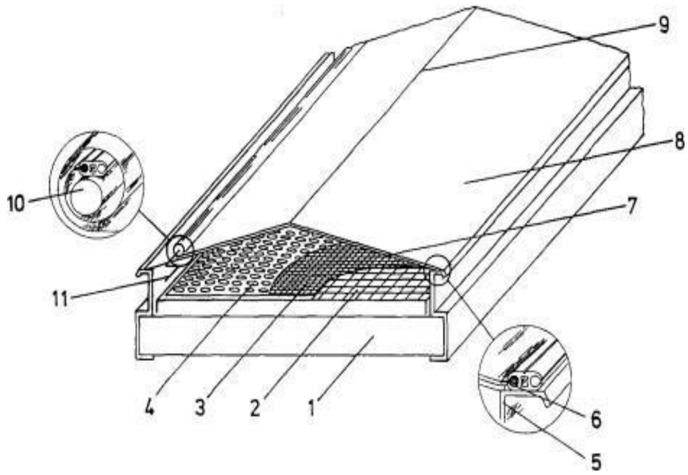

Figure II. 2: Drying tunnel: (1) back insulator,(2) wire mesh,(3) plastic net ,(4) product to be dried,(5)metal frame ,(6) fastening plastic profile,(7) metal strip for supporting the sheet ,(8) air bubble plastic sheet,(9) string for supporting the sheet ,(10) meta

M.A. Hossain, et al. (2004), described an optimization study of a solar tunnel dryer for drying chilli peppersin Bangladesh. The authors used simulations and economic models to determine the best dimensions for the collector and drying unit to minimize color loss. Designed to supply hot air tothe drying tunnel with two small fans driven by a photovoltaic unit. The study confirms the possibility of optimizing solar tunnel dehydrators to improve the efficiency and economic viability of drying chilli peppers in Bangladesh.

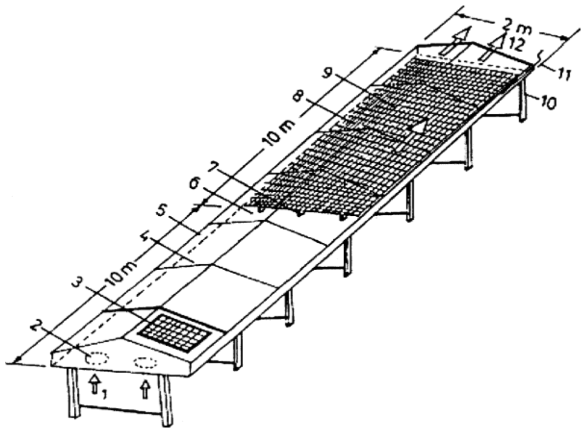

Figure II. 3: Solar tunnel drier: (1) air inlet; (2) fan; (3) solar module; (4) solar collector; (5) side metal frame; (6) outlet of the collector; (7) wooden support; (8) plastic net; (9) roof structure for supporting the polyethylene cover;(10) base structure for

H.H. Chen, et al. (2004), developed a closed-type dryer associated with a photovoltaic system (PV). PV module used as an energy supply that complements the dryer. The transparent dry- ing cabinet was designed to reduce reflection of direct sunlight and provide extradirect solar heating. and results showed that the dried lemon slices had better general levels of quality in terms of sensory parameters.

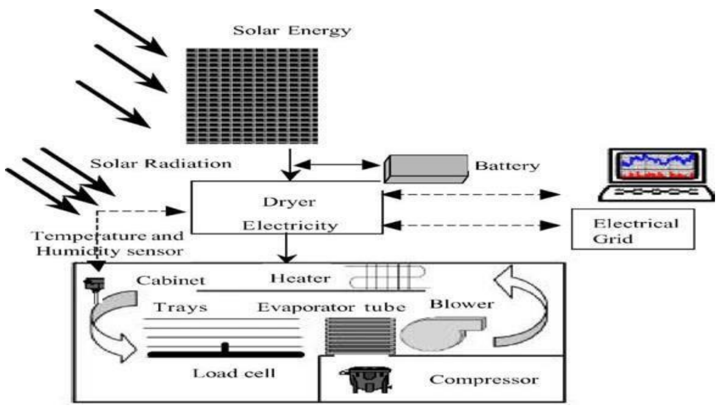

Figure II. 4: Schematic diagram of the experimental closed type solar dryer associated with the PV module as a complementary electrical power source and its dehumidification system

B.K. Bala et al. (2005), discussed the application of a solar tunnel drier to dry jackfruit bulbs and leather. Thy utilize two direct-current fans powered by a photovoltaic module to supply hot airinto the drying tunnel, with a capacity of 120-150 kg of fruits. A neural network model is used toforecast the drier's efficiency and predict its performance using a predictive optimal control algorithm.

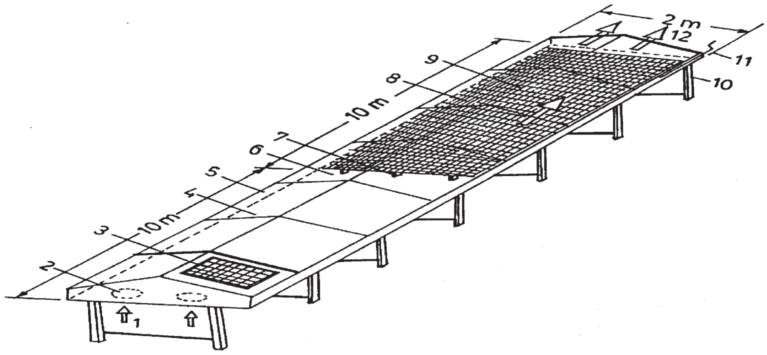

Figure II. 5: Solar tunnel drier: (1) air inlet; (2) fan; (3) solar module;(4) solar collector; (5) side metal frame; (6) outlet of the collector;(7) wooden support; (8) plastic net; (9) roof structure for supporting the plastic cover; (10) base structure for suppor

S. Janjai et al. (2005), investigated the performance of a greenhouse solar dryer for drying bananas. Thedryer had a concrete floor with a polycarbonate cover and was ventilated by three fans powered by a 50-watt solar cell module. Results showed that 50 kg of fresh bananas can be dried in 3days. It concluded that the PV-ventilated greenhouse dryer is an effective method for dri drying bananas.

Figure II. 6: The greenhouse solar dryer.

B. K. Bala et al. (2006), investigated the performance of solar tunneldryer for drying fish. The dryer consisted of a flat plate collector covered in clear plastic and a drying tunnel connected in series. The drying tunnel received hot air directly from the collector using four DC fans, which were powered by two 40-watt solar modules. The dryer has the capacity to dry up to 150 kg of fish.

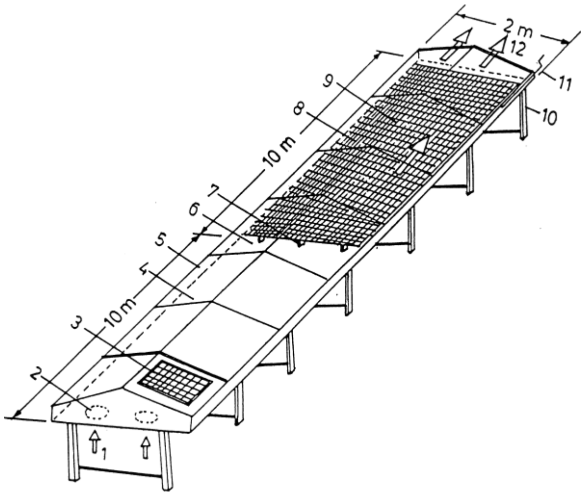

Figure II. 7: Solar tunnel dryer: 1. air inlet, 2. fan, 3. solar module, 4. solar collector, 5. side metal frame, 6. outlet of the collector, 7. wooden support, 8. plastic net, 9. roof structure for supporting the plastic cover, 10. base structure for supporting.

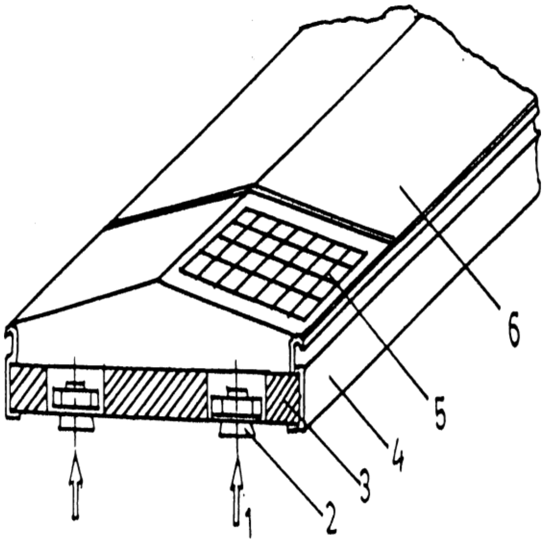

Figure II. 8: Solar collector: 1. air inlet, 2. fan, 3. back side insulator, 4. side metal frame, 5. solar module, 6. transparent plastic cover.

P. Barnwal et al. (2008), examined the convective mass transfer of grapes when dried in a photothermal hybrid dryer built in a greenhouse under forced mode. The dryer is self-sustaining and is made by integrating a greenhouse with two photovoltaic units that provide DC electrical power to drive a DC fan for forced mode operation and also produce convective heat inside the greenhouse from a non-fillable area, which helps in drying the crops.

Figure II. 9: Hybrid photovoltaic thermal (PV/T) integrated greenhouse dryer.

Figure II. 10: Grape photographs after drying (GR-I).

S. Janjai et al. (2009), studied the performance of a PV-ventilated solar greenhouse dryer for drying peeled longan and banana, the dryer consisted of a parabolic roof structure covered with polycarbonate plates on a concrete floor, with three fans powered by a 50-W PV module to ventilate the dryer. They found that the drying time for peeled longan was 3 days, and for banana, it was 4 days.

Figure II. 11: Pictorial view of the greenhouse solar dryer

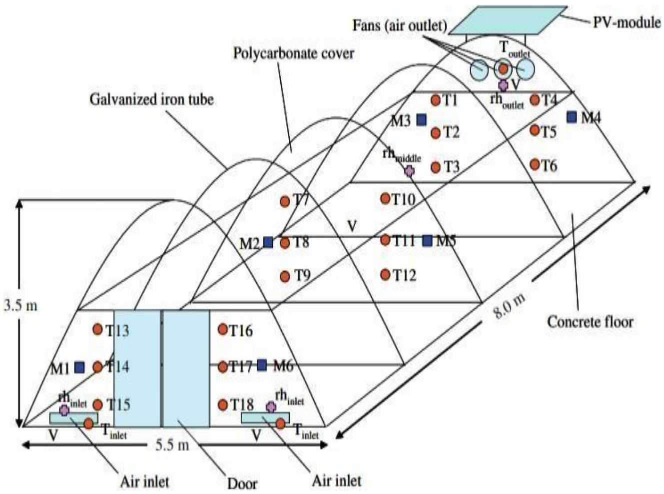

Figure II. 12: The structure and dimension of the dryer and the positions of the thermocouples (T), hygrometers (rh), air speed (V) and product samples for weights (M).

S. Sultana et al. (2009), compared the drying performance of two methods, the rotary drying and the solar dryer, to produce dried fish products using three types of marine fish. Temperature and humidity measured during the drying process, the entire system is placed horizontally on a raisedplatform, air is supplied by four DC fans driven by two photovoltaic units as air is passed over the products.

Figure II. 13: Plate No. 1. Rotating dryer without fish.

Figure II. 14: Plate No. 3. Solar tunnel dryer used for drying.

G. Romano et al. (2009), this research aims to measure changes in apple and carrot cutting temperatures, solar radiation and air moisture distribution during rotation and drying. It includes two photovoltaic (PV) modules connected to a DC fan, which can be operated at either half or full capacity. The energy required to remove apples and carrots was 3300.19 and 7428.28 kJ/kg, respectively.

Figure II. 15: Picture of the applied solar dryer**.**

J. Kaewkiew et al. (2011), investigated the performance of a large-scale greenhouse type solar dryer for drying chilli, with nine DC fans powered by three 50 W solar cell modules. It was found that five hundred kilograms of chilli with a moisture contentof 74% (wb) were dried within 3 days, while the natural sun dried needed 5 days. And good quality was obtained.

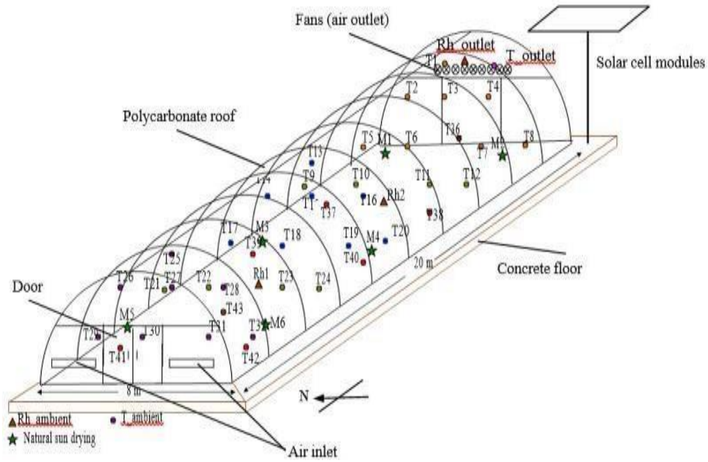

Figure II. 16: The positions of the thermocouples (T) and measurements of relative humidity (Rh) and weights of the product samples (M).

C.N. Anyanwu et al. (2012), described the design and experimental performance evaluation of a photovoltaic (PV)-powered solar drying system suitable for processing export-grade cassava at the National Centre for Energy Research and Development, University of Nigeria, Nsukka. The system comprises an 8.40 m2 roof-type solar collector, a drying unit with five trays, and a PV- powered 90 WAC blower.

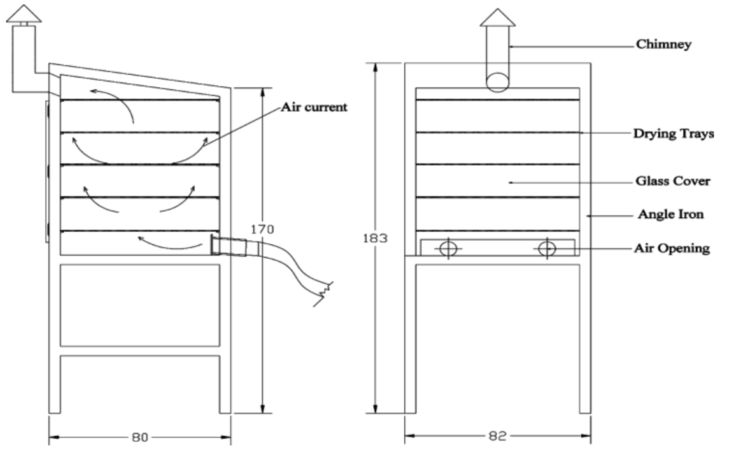

Figure II. 17: Various views of the solar dryer**.**

İ.Ceylan et al. (2013), designed and manufactured a solar dryer that uses photovoltaic cells to assist the drying process, using tomatoes as a test material, a blower fan was used to heat and force the drying air, and photovossaics were used to power the fan and charge the batteries. The batteries were then used to generate the halogen lamps at night. Measurements of various factors were taken during the drying process to analyze the energy of the solar dryer.

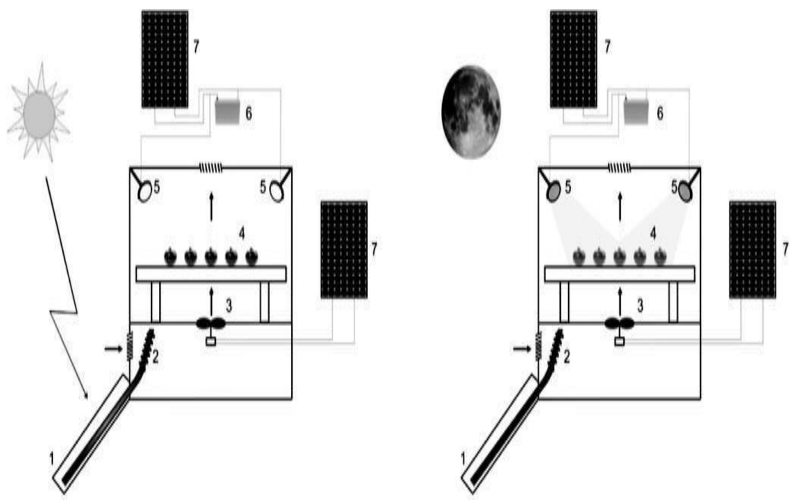

Figure II. 18: The new design solar dryer assisted PV cells. ‘‘A’’ signifies use in daylight and ‘‘B’’ signifies use at night. 1. Heat pipe collector, 2. Fins of thecollector, 3. Circulating.

L. Bennamoun (2013), integrated photovoltaics into drying systems to improve efficiency and reduce reliance on electrical energy, resulting in solar harvesting efficiencies of up to 70%. Photovoltaics are used to recycle electrical energy consumed by other components of the drying system, such as fans, resulting in greater use of integrated photovoltaic dryers for food and herb drying.

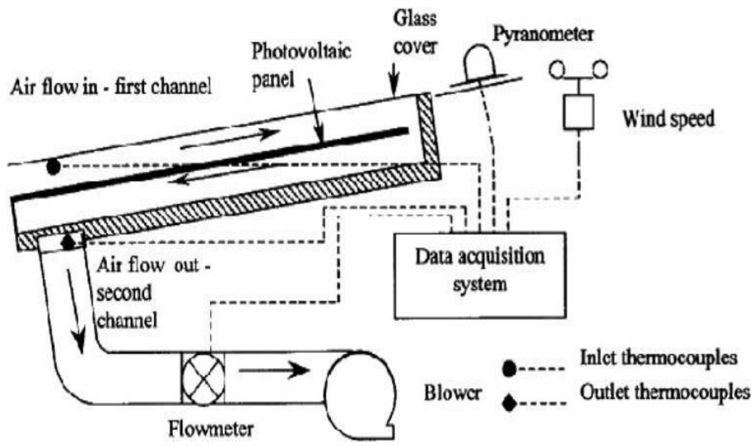

Figure II. 19: Double-pass PV=T solar collector.

I. Farkas, (2013). explored the advantages of utilizing a solar dryer for drying grain, fruit, and alfalfa. The modular concept is suggested for the appropriate design of the solar dryer, which consists of a dry chamber, photovoltaic module, fan, and solar air collector unit. The solar dryingequipment operates year-round, leading to a reduction in the payback time of the entire installation.

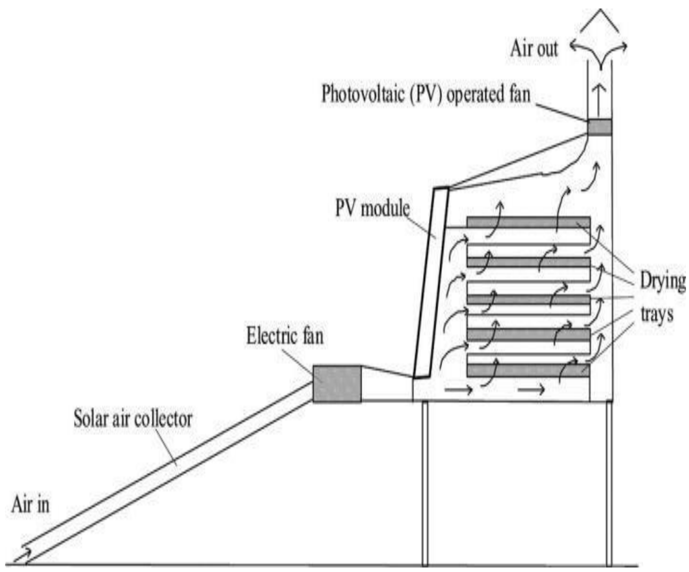

Figure II. 20: Scheme of the modular solar tray dryer.

A.Kumar et al (2014), reviewed the design, construction and operational principles of solar drying systems is presented. Moomba has developed a solar grain dryer incorporating a photovoltaic powered DC fan, providing a low cost and environmentally friendly solution for farmers to dry their crops. It was published in the Journal of Renewable Energy.

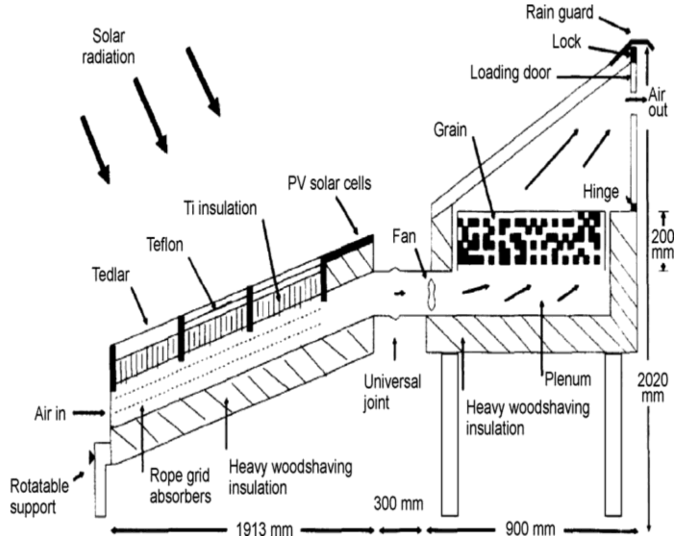

Figure II. 21: An illustration of solar-grain drier incorporating a photovoltaic- powered D.C. fan. Reprinted from Renewable Energy, 6(7), Mumba, Development of a photovoltaic powered forced circulation grain dryer for use in the tropics, pp. 855–862, Copyright 1995.

S. Thongsan et al. (2017), developed a solar drying technology by integrating a solar collectorand photovoltaic (PV), with a thermoelectric generator (TEG) module. They found that the temperature at the back side of the solar collector decreased with an increase in the power produced by the TEG module, and that the solar collector was able to produce hot air temperatures of 70-80 OC. The system was also equipped with a blower that could control theair flow rate.

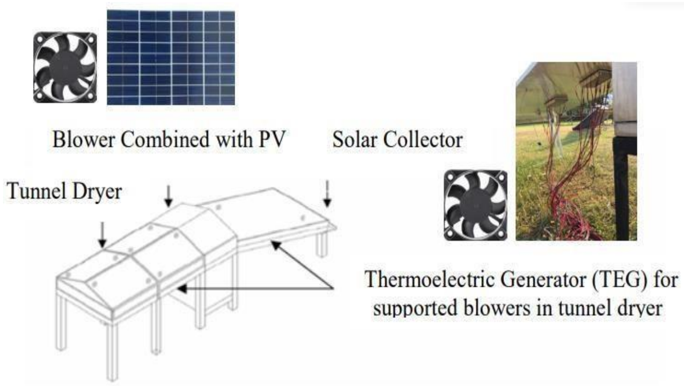

Figure II. 22: Concept of Development of solar collector combined with thermoelectric.

M. Eltawil et al. (2017), developed a solar PV system-powered dryer for potato chips using a mixed- mode solar tunnel dryer (STD) with an axial dc fan and a flat plate solar air collector. The dryer produced potato chips with safe moisture levels and reduced frying time, The best chips color was achieved using 1% sodium meta-bi-sulphite and a black thermal curtain, making the STD suitable for rural areas.

Figure II. 23: Experimental setup of solar PV powered enhanced tunnel dryer for potato chips. a) without shading the potato chips, b) with shading the potato chips (black thermal curtain).

V. Saini et al. (2017), proposed a greenhouse solar dryer with photovoltaic cell technologies, which are used to drive a DC fan and provide a shading effect to avoid crop discoloration and excess storage power. Several parameters were evaluated from an environmental point of view for different climatic conditions in New Delhi, India, and MATLAB 2013a was used to calculate various parameters.

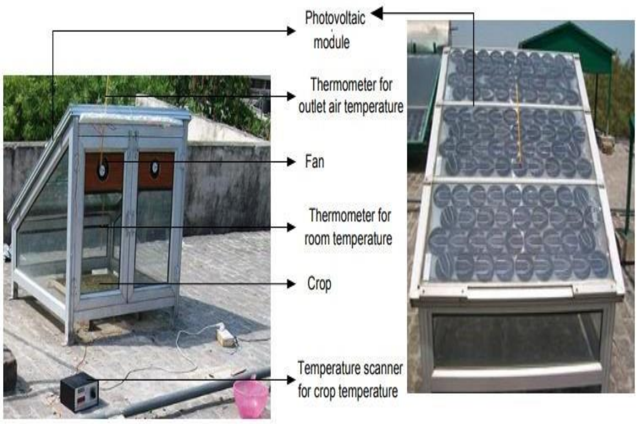

Figure II. 24: Photovoltaic integrated greenhouse dryer.

M. A. Eltawil et al. (2018), developed a hybrid portable solar tunnel dryer with a thermal curtain to improve the drying performance of mint by using a solar photovoltaic system and a flat solar collector,and an axial direct current fan for forced mode ventilation. Results showed that the drying time decreased and the quality of dried mint was higher.

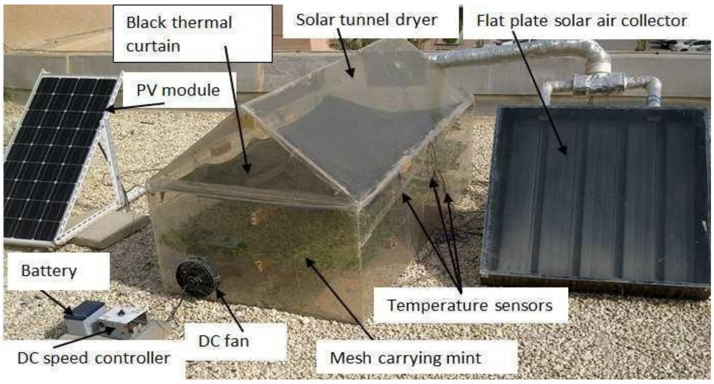

Figure II. 25: Experimental setup of solar tunnel dryer enhanced by PV system and flat plat.

S. Poonia et al. (2018), described the drying kinetics of ber (Zizyphus maur- itiana) fruit.The hybrid system enables combined production of electrical energy and thermal energy from photovoltaic panel and flat plate collector.The dryer is composed of a collector unit, drying chamber,DC fan,PV panel and PCM chamber for thermal storage, with a PV module at the left side to operate the DC fan.

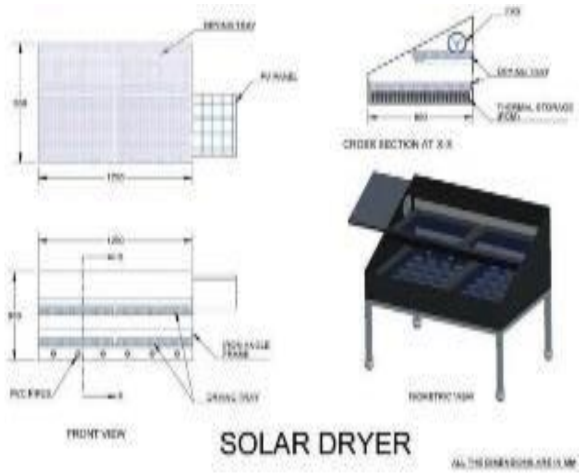

Figure II. 26: Schematic diagram of photovoltaic/thermal (PV/T) hybrid solar dryer.

Figure II. 27: Schematic diagram of photovoltaic/thermal (PV/T) hybrid.

A. Mathew et al. (2018), proposed a photovoltaic assisted solar drying system with a parallel flow groove type collector. When photovoltaic energy source is not present, a funnel with a ventilatorturbine is added in the system. The study shows that an increase in solar radiation intensity will increase air temperature and flow rate.

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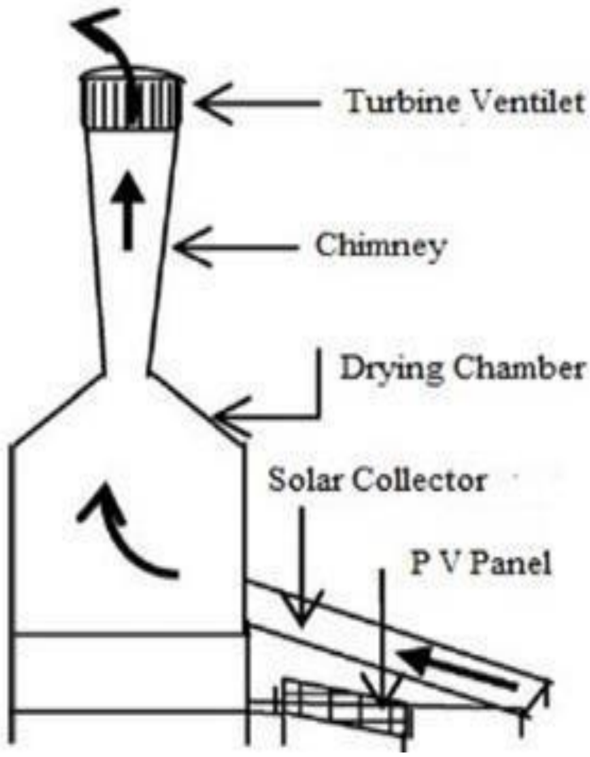

Figure II. 28: PV assisted solar drying system.

M. A. Eltawil et al. (2018), developed a solar PV system-powered dryer for potato chips using a mixed-mode solar tunnel dryer (STD) with an axial dc fan and a flat plate solar air collector. The dryer produced potato chips with safe moisture levels and reduced frying time, the best chips color was achieved using 1% sodium meta-bi-sulphite and a black thermal curtain, making the STD suitable for rural areas.

Figure II. 29: Experimental setup of solar PV powered enhanced tunnel dryer for potato chips. a) Without shading the potato chips, b) with shading the potato chips (black thermal curtain).

E. A. Mewa et al. (2019), examined the drying kinetics of beef in a solar tunnel dryer, which was powered by a single photovoltaic solar module driving two direct current fans. Results showed that the temperature profile increases with solar radiation and decreases with high moisture content, and that the page model was best suited to represent the drying properties.

Figure II. 30: Pictorial view of the solar tunnel dryer from the collector end.

P. Hempattarasuwan et al. (2019), investigated the performance of a parabolic greenhouse-type solar dryer for drying cayenne pepper in Nan, northern Thailand. It had a base area of 6.0 m × 8.2 m and a height of 3.25 m, with a loading capacity of 100-200 kg. It was ventilated by three DC fans powered by a 50-Watt solar cell module. The produce was placed on trays with a wire mesh baseand located on steel supports.

Figure II. 31: Parabolic solar dryer used in Nan. Rear of the dryer with the three-exhaust fan.

V. Subbian et al. (2019), evaluated the performance of a solar tunnel dryer for drying beef with a 200-watt photovoltaic panel, where air enters through the collector by a DC blower powered by photovoltaic cells. Desiccant manufactured with locally available materials and tested by drying experiments in Tamil Nadu., India. In general, the study evaluated the performance of the solar dryer using different statistical methods.

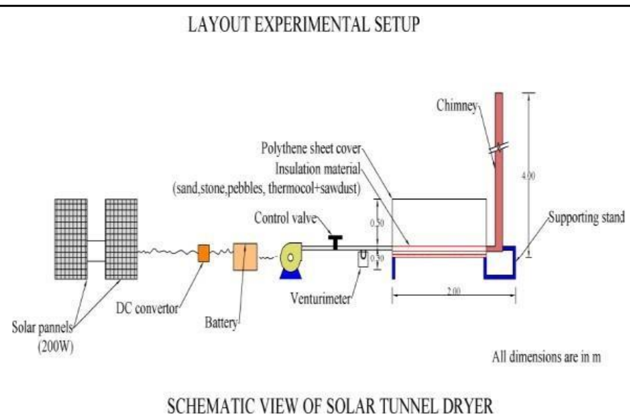

Figure II. 32: Shows a Schematic View of the Solar Tunnel Dryer with dc Blower.

Figure II. 33: Photographic View of Solar Tunnel.

P. Chauhan et al. (2020), investigated the thermal performance of the photovoltaic-ventilated a mixed-mode greenhouse solar dryer with automatic closed-loop control for drying Ganoderma. They found that the drying rate was higher in the solar dryer than in traditional drying.

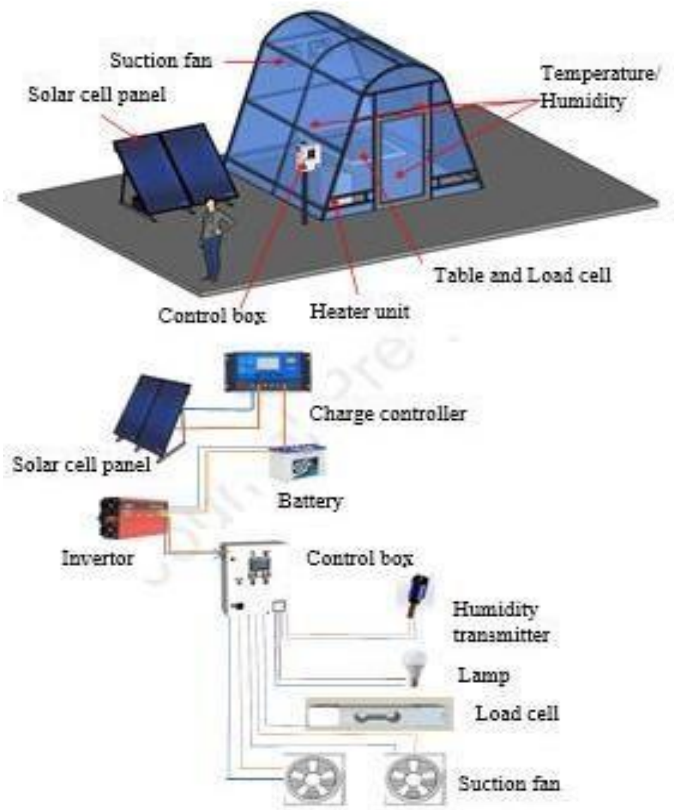

Figure II. 34: Pictorial view and load diagram of the photovoltaic- ventilated greenhouse solar dryer.

N. Nwakuba et al. (2020), investigated the performance of a parabolic greenhouse-type solar dryer for drying cayenne pepper in Nan, northern Thailand. It had a base area of 6.0 m × 8.2 m and a height of 3.25 m, with a loading capacity of 100-200 kg. It was ventilated by three DC fans powered by a 50-Watt solar cell module and placed on trays with a wire mesh base and steel supports.

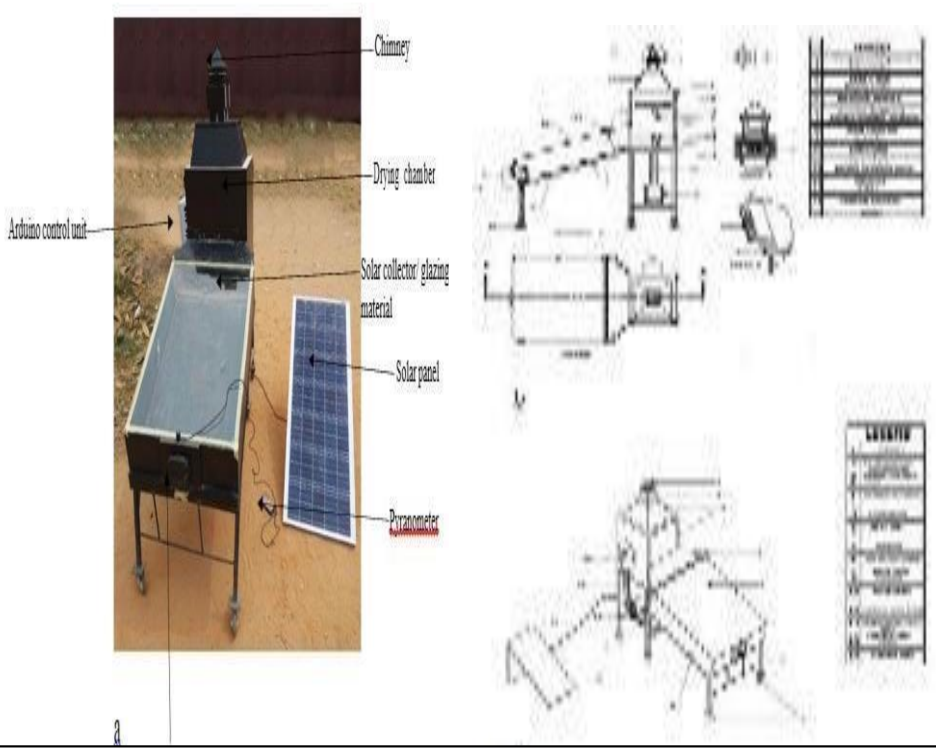

Figure II. 35: (a) Pictorial presentation of the HSED. (b) Sectional outlook of the HSED. (c) Isometric outlook of the HSED setup.

P. Pankaew et al. (2020), compared the performance of a large-scale solar dryer with and without a phase-changed material (PCM) thermal storage system, as well as an open sundryer fordrying chili peppers.were installed at Silpakorn University in Thailand.Nine 14-watt DC axial fans powered by three 50-watt solar cell modules are installed in the back wall of each dryer to suck the moist air inside the dryer into the surrounding environment.

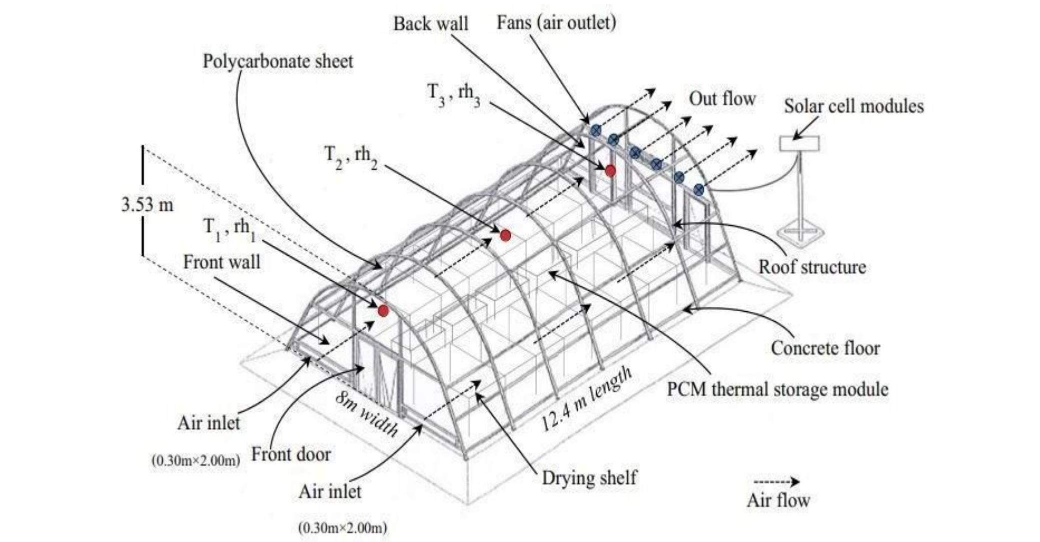

Figure II. 36: Structure of the large-scale greenhouse solar dryer integrated with PCM thermal storage system and the positions of the measurements (Ti = temperature at position i, i = 1, 2, and 3 rhi = relative humidity at position i, i = 1, 2,

M. M. Azam et al (2020), aimed to develop a solar-powered hybrid greenhouse dryer (GD) with a photovoltaic system and a solarcollector for post-harvest drying of tomatoes, photovoltaic. The system dre a fan to improve the drying process. The researchers used mathematical modeling to evaluate the thermal performance of the system.

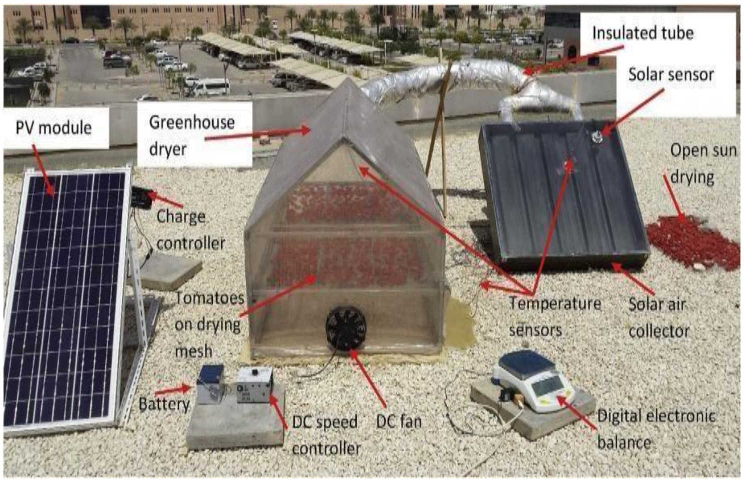

Figure II. 37: Experimental setup of solar PV operated the greenhouse dryer for drying tomatoes.

T. M. Ismail et al. (2020), focused on investigating the performance of a solar tunnel dryer integratedr with a flat-plate solar air collector for drying (RDF), consisting of a solus flyer, duct system,flat plate adaption, solar panels, inverter with console, centrifugal blower, fan, and testability. Photovoltaic panels convert sunlight to electricity to power the centrifugal condenser and fan in the solar Tunnel dryer, and analyze the efficiency of the solar collector and drying process.

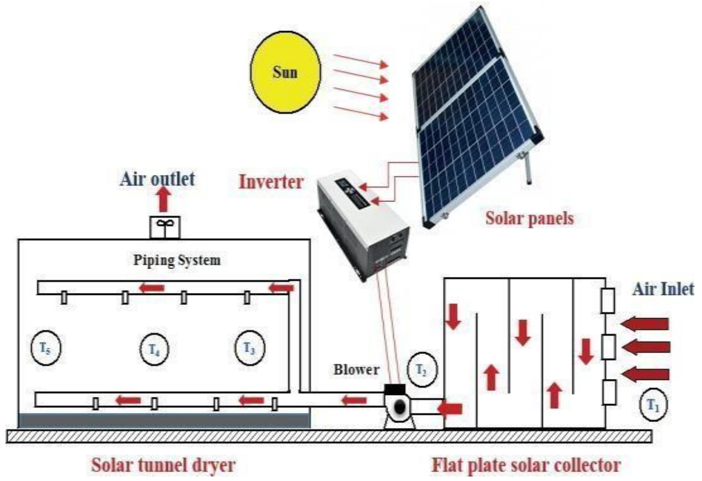

Figure II. 38: Schematic diagram of experimental set-up.

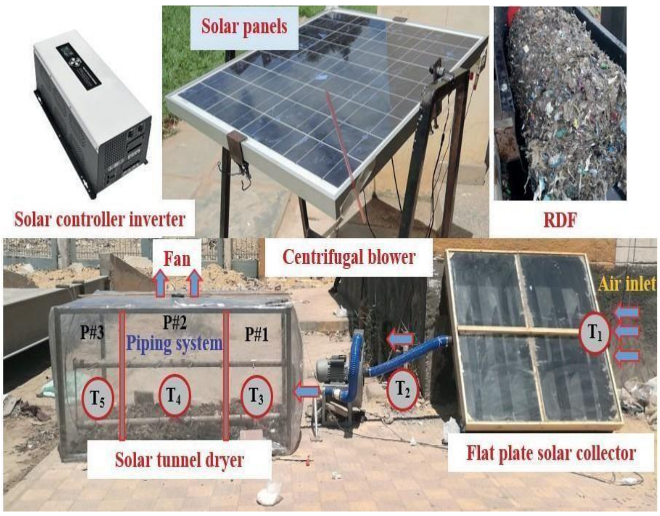

Figure II. 39: Photograph of experimental set-up.

L. F. Hidalgo et al. (2021), developed a solar dryer with the help of a photovoltaic unit to dry green onions, which has high efficiency and low energy consumption. The device provides electrical power to eight coolers, allowing for the renewal of air and the preservation of green color. This highlights the potential of using solar dryers to promote sustainable agriculture.

Figure II. 40: Direct solar dryer**.**

Figure II. 41: Green onion fresh leaves and the stalks that were discarded. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

D. Barisik Marasli et al. (2021)., Used a solar cells to convert sunlight into electrical energy to operate a DC fan or assist a solar collector. PVT systems are available in two configurations: a single collector and two separate systems. Solar dryers do not include a separate solar collector, but use solar energy by their structure.

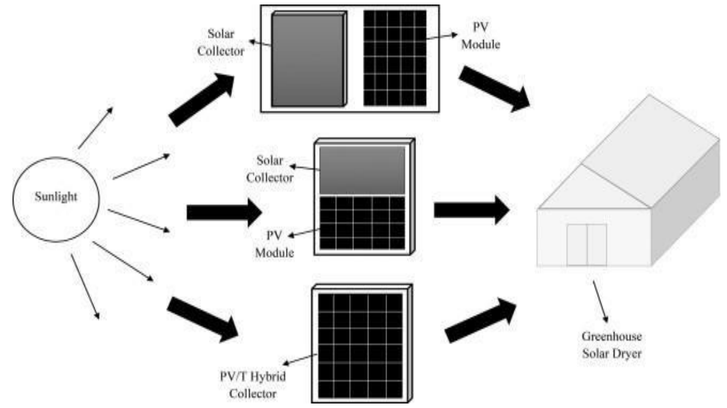

Figure II. 42: .(a) PV and solar collector assisted (PV þ T);(b) PVT collector assisted; (c) hybrid PV/T collector assisted

S. Murali et al. (2022), evaluated the drying properties, modeling of drying behavior, and performance of a PV-powered semi-cylindrical solar thermal dryer with a mobile alarm system using shrimp. The dryer was constructed using UV stabilized polyethylene film, CPVC tubes andGI frames and was connected to the photovoltaic panel. Mobile alarm system with Arduino UNO, load sensor and GSM.

Figure II. 43: Solar tunnel dryer (a) External view (b) Internal view (c) PV panel (d) Battery- charge controller.

Figure II. 44: Mobile alert system for shrimp drying in a solar tunnel dryer (a) Aurdino UNO display (b) Load cell inside dryer (c) SMS alerts in mobile.

S. Kondwani et al. (2022), examined a convection forced thermal solar dryer for mango drying with a 10W solar panel connected to fans. The air temperature in the drying chamber caused highdrying rates, resulting in 13.7% wetness. The use of a vertical solar collector stabilized the drying room air temperature and made the dryer more compact.

Figure II. 45: Solar dryer front view showing the drying chamber exit fan at the apex of the greenhouse.

II.2. Problem formulation: Design and built a new solar dryer assisted by photovoltaic cell

In conclusion, based on the aforementioned presentation, we can affirm that solar drying using photovoltaic (PV) technology is a suitable method for drying various agri-food products. This approach has undergone several enhancements to meet the requirements of energy consumption and the final product's quality. The utilization of PV technology in solar drying has proven to be effective, offering improved energy efficiency and meeting the demand for high-quality dried products. The continuous advancements in PV-based solar drying techniques have successfully addressed the challenges related to energy consumption and product quality, making it a viable option for drying agri-food products.

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CHAPTER III

Experimental Setup and System Operation

III.1. Introduction

It aims to assess the effectiveness of using this technology to improve the efficiency and sustainability of herb drying processes for different times throughout the day. The main objective of this research is to investigate the performance of the new solar dryer assisted by photovoltaic cell in terms of energy efficiency, drying time, and product quality. By combining the advantages of both solar drying and PV technology, we aim to create a sustainable and cost-effective solution for herb drying, especially in regions with limited grid electricity. The use of an Arduino-controlled cart provides an added level of control over the drying process. Overall, this study aims to provide insights into the potential of using solar dryers with PV-powered fans and Arduino-controlled for improving the sustainability and efficiency of herb drying processes at different times of the day.

III.2. Experimental Setup

The picture shows a solar dryer powered by solar energy (PV) shown in **Figure III. 1**.
It consists of a direct solar dryer, solar panels, a fan and an electronic board. The experimental setup consists of the following:

- ❖ Solar dryer
- ❖ Solar dryer with Controlling Circuit
  - Electronic board (Arduino , LCD , Key bad , Relay, Sensor)
  - Ventilated
  - Resistance
  - Solar panels (PV)
- ❖ Measuring device and instruments
  - Pyranometre
  - Sensor

III.2.1. Solar dryer

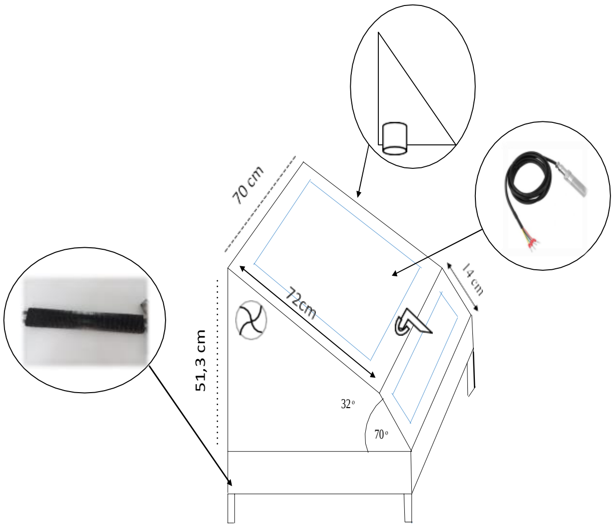

Figure III. 1 : Photo of a solar dryer.

III.2.2. Description of the Experimental prototype

In this section, we will provide a general description of the solar dryer prototype examined within the scope of our master's thesis. This solar dryer prototype was designed, constructed, and developed in the platform of the Unit of Applied Research for Renewable Energies (URAER) in Ghardaia; the solar dryer is constructed using iron as the primary material, with dimensions measuring 72cm in length, 70cm in width, and 51.3cm in height. The structure is designed to provide compact and efficient drying space. The top of the dryer has a slanted angle of 32 degrees to maximize sun exposure.

To facilitate the drying process, the solar dryer includes a transparent cover made of glass. This angled glass lid allows ample sunlight into the dryer and promotes efficient drying.

For proper airflow and ventilation, the solar dryer is equipped with a fan. This fan helps circulate the air inside the dryer, which facilitates the evaporation of moisture from the drying products. The fan is connected to a photovoltaic (PV) panel, harnessing solar energy for its operation. In addition, the solar dryer has a vent to allow fresh air in and maintain optimal airflow during the drying process **(Figure.III.2).**

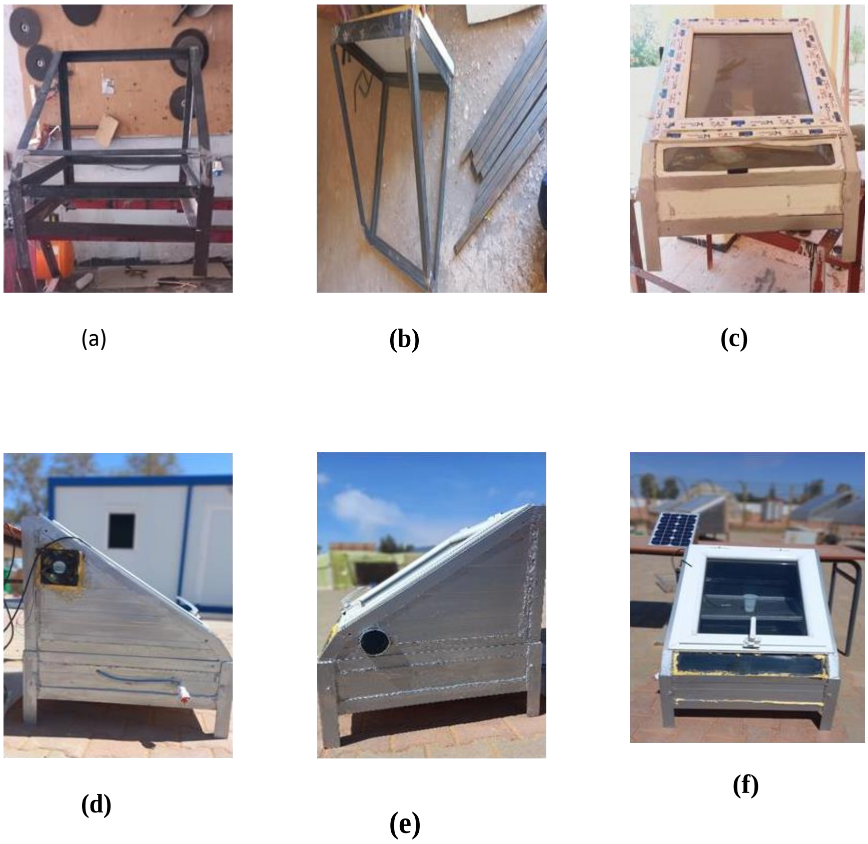

Figure III. 2: Description of the Experimental prototype (new solar dryer).

III.2.3. Solar Dryer with Controlling Circuit

The above solar dryers' parameters are tested and controlled using Arduino as shown below:

III.2.3.1. **BLOCK DIAGRAM**

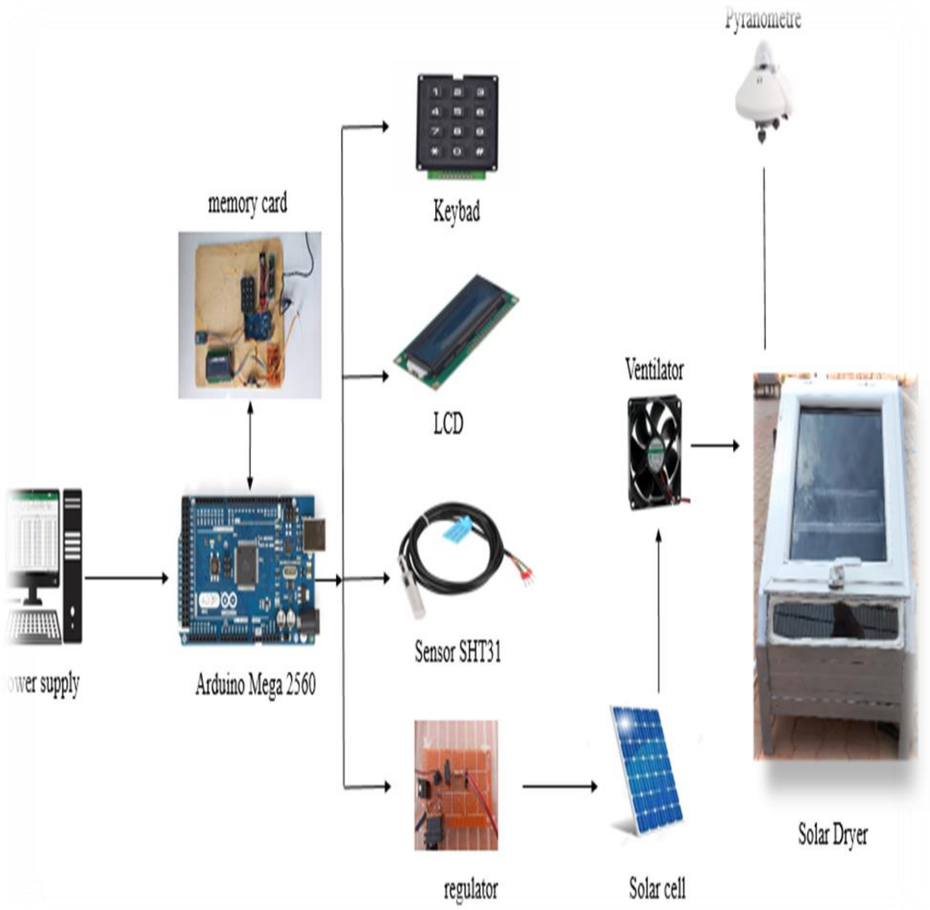

Figure III. 1: Block diagram.

III.2.3.2. **Controlling Circuit**

a. Electronic board (Arduino , LCD , Keybad , Relay, Sensor)

An electronic board, such as the Arduino, can be connected to various components such as an LCD, keypad, and contactor to create a functional electronic system. Here is some general information about each component:

- **Arduino Mega 2560**

The Arduino Mega 2560 offers an extensive number of digital and analog I/O pins, making it suitable for projects that require a large number of inputs and outputs. It has a higher flash memory and RAM compared to other Arduino boards, allowing for more complex and memory-intensive applications. The 16 MHz clock speed ensures efficient execution of code, and it can be powered through a range of input voltages.

Figure III. 4: Arduino Mega 2560.

Table III. 1: Specifications of Arduino Mega.

Operating Voltage	5V
Input Voltage	6-20V
Digital I/O	54 (of which 15 provide PWM output)
Analog Input	6
Length	101.52 mm
Width	53.3mm
Weight	37g
DC Current per I/O Pin	20 mA
Clock Speed	16 MHz

- **Simplified diagram of the Arduino Mega board**

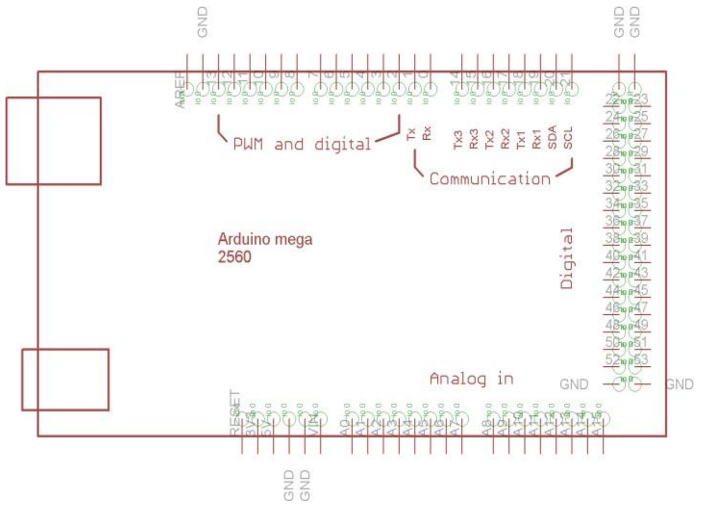

Figure III. 5: Simplified diagram of the Arduino Mega.

- **Powering the Arduino Mega 2065**

The Arduino Mega 2065 can be powered either through a USB connection or an external power source. The power selection is automatic.

The external power can be supplied from an AC-DC adapter or a battery. The adapter can be connected by plugging a 2.1 mm plug into the power jack of the board, or from a battery connected to the GND and Vin pins.

The processor can operate on an external power supply ranging from 7 to 20 V. However, if the voltage is below 7 V, the 5V pin may provide less than 5 V, potentially causing instability in the processor. If the voltage exceeds 12V, the regulator may overheat and damage the board. The recommended voltage range is between 7 and 12 volts for optimal performance and safety of the Arduino Mega 2065.

➢ LCD (Liquid Crystal Display)

Table III. 2: Specifications of liquid Crystal display	
Operating Voltage	5 V DC
Module Dimension	60 mm x 36 mm x 15 mm
Viewin Area Size	64.5 mm x 16 mm
Displays	2lines (x16) characters

Figure III. 6: Lcd1602A.

➢ Keypad

Table III. 3: Specifications of Keypad	
Type	Keypad4×3 buttons
Rows	4 as inputs
Columns	3 as outputs

Figure III. 7: Keypad4×3.

- **Relay**

Table III. 4: Specifications of Relay	
Type	SSR-60 DA
Operating Voltage	3-32VDC 24-380VAC
Quantity	01

Figure III. 8: Relay.

- **Sensor SHT31 (**Temperature, Humidity)

Table III. 5: Specifications of Sensor SHT31	
Type Sensor	Digital SHT31 High Precision Sensor
Humidity Ranger	0-80%RH
Temperature ranger	40,125℃
Humidity accuracy	±0.01%RH
Temperature accuracy	±0.3℃

Figure III. 9: Sensor.

b. Ventilator

Table III. 6: Specifications Ventilator	
Power	4.8 W
Volt	12 v / DC
Current	1.6 A

Figure III. 10: Ventilator.

c. Resistance (two resistance)

Table III. 7: Specifications Resistance	
power	1000 w
volt	238 V

Figure III. 11: Resistance.

e. Solar panel (PV)

Table III. 8: Specifications Solar panel	
Max power	10 watt
Current Rated	0.6 A
Short CKT	0.68 A
Voltage Rated	16.8 V

Figure III. 12: Solar panels (PV**).**

III.2.4. Measuring Device and Instrument

Parameter is measured in this study:

III.2.4.1. Measurement of solar radiation:

A radiometric station consists of two parts: a fixed part which consists of an EKO pyrometer for measuring global radiation on a horizontal plane, and an EPPLEY differential pyrometer for measuring irradiance on an inclined plane of 32° facing south. A mobile part (solar tracking system) is equipped with a pyrheliometer pointed towards the solar disk to measure direct radiation, and an EKO pyrometer with a sunshade ball for measuring diffuse illuminance on a horizontal plane.

Figure III. 13: Radiometric station**.**

III.2.4.2. Sensor SHT31 (in the page72).

III.2.5. Solar Dryer with programming Circuit:

a. LCD code

```
void  show onoff()

{

  // Code for displaying information on the LCD screen

}



void  showTempAndHumidity()



  // Code for displaying temperature and humidity on the LCD
screen

}



void  showfan()
```

Figure III. 14: code LCD

- The show_onoff() function is responsible for displaying information on the LCD screen related to on/off status.
- The showTempAndHumidity() function displays temperature and humidity information on the LCD screen.
- The showfan() function displays the fan speed on the LCD screen.
- These functions are placeholders where you can add your specific code to interact with the LCD screen and display the desired information.

b. Keypad Code

```
// Code for keypad functionality
for (int i = A9; i <= A15; i++)
{
for (int j = A9; j <= A15; j++)
{
if (i != j)
{
pinMode(i, OUTPUT);
pinMode(j, INPUT_PULLUP);
```

Figure III. 15: code Pin Configuration (Keypad)

- The commented code block demonstrates an example of configuring pins A9 to A15 as OUTPUT and INPUT_PULLUP.
- The active code block is for the keypad functionality.
- The nested for loops iterate over output and input pins to detect button presses on a keypad. Each output pin is set as OUTPUT (pinMode(i, OUTPUT)), and each input pin is set as INPUT_PULLUP (pinMode(j, INPUT_PULLUP)).
- The output pins are briefly set to a low state (digitalWrite(i, 0)) to simulate button presses.
- If a button press is detected (digitalRead(j) == 0), the corresponding output and input pin numbers are printed to the serial monitor.
- This code can be modified to match the specific configuration and behavior of your keypad.

c. Relay code

```
void loop()

{

 unsigned long currentMillis = millis();



 if (currentMillis >= Taff_next)

 {

  // Code for timer functionality



  Taff_next = millis() + 1000;

 }



 // Code for other functionalities or actions
```

Figure III. 16: Relay code

- The loop() function is the main loop that runs continuously in the program.
- It uses the millis() function to get the current time in milliseconds and stores it in the currentMillis variable.
- The condition if (currentMillis >= Taff_next) checks if the specified time interval has elapsed.
- Inside the condition, you can add code for the desired timer functionality that needs to be executed.
- The line Taff_next = millis() + 1000; updates the value of Taff_next to schedule the next timer event after 1 second.
- The setup() function is called once at the beginning of the program and is used for initial setup tasks.

d. **Sensor SHT30 Code**

```
SHT31D result =
sht3xd.readTempAndHumidity(SHT3XD_REPEATABILITY_LOW
, SHT3XD_MODE_CLOCK_STRETCH, 50);

//SHT31D result =
sht3xd.readTempAndHumidity(SHT3XD_REPEATABILITY_HIG
H, SHT3XD_MODE_POLLING, 50);
```

Figure III. 17: code Sensor SHT31

- TheSHT31Dresult=sht3xd.readTempAndHumidity(SHT3XD_REPEATABILITY_LOW, SHT3XD_MODE_CLOCK_STRETCH, 50); line reads temperature and humidity data from a sensor (SHT31D).
- The result of the sensor reading is stored in the result variable, which can then be used to extract temperature and humidity values.

III.2.6. The wiring with Arduino (by fritzing)

- The wiring Arduino with LCD

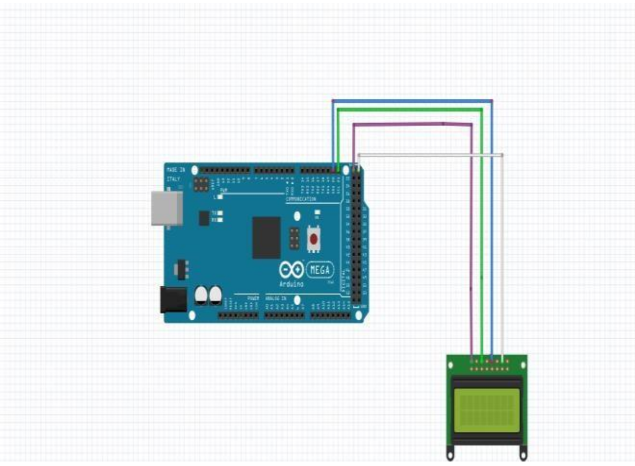

Figure III. 18: Wiring of Arduino with LCD

- The wiring Arduino with Keypad

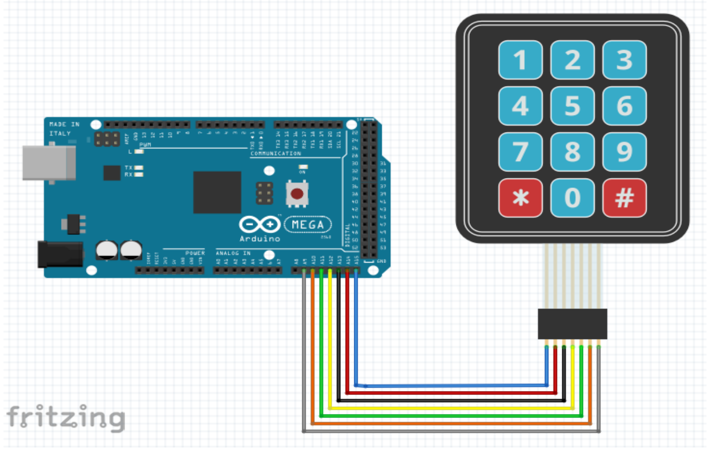

Figure III. 19: Wiring of Arduino with Keypad

- The wiring Arduino with Sensor

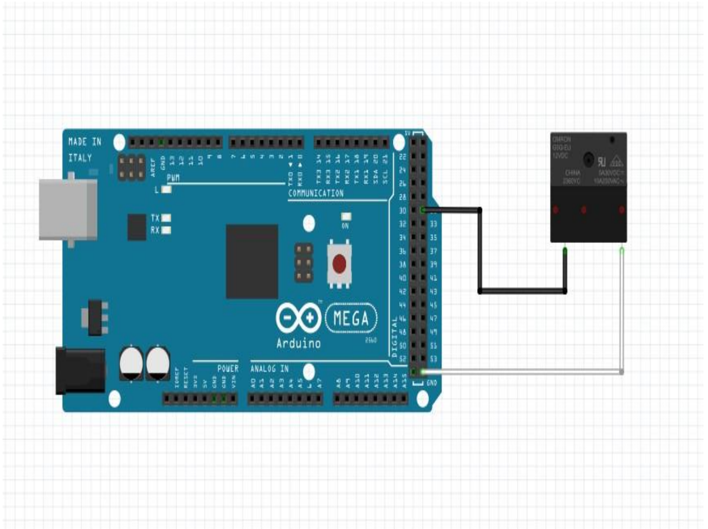

Figure III. 20: Wiring of Arduino with Sensor

The wiring Arduino with Relay

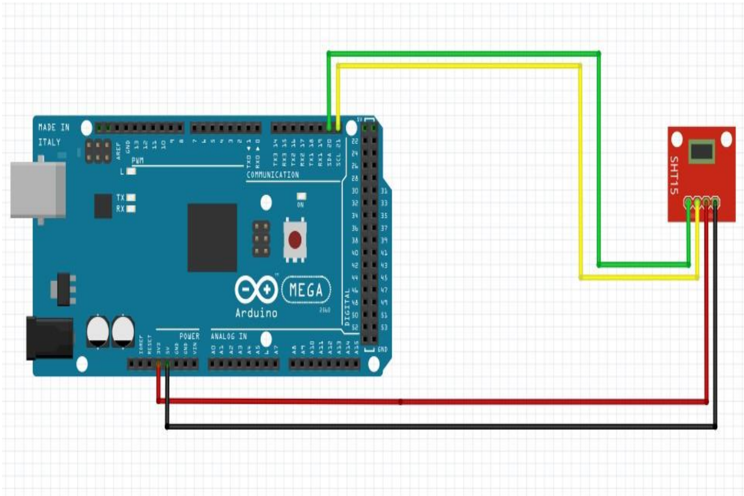

Figure III. 21: Wiring of Arduino with Relay

The wiring Arduino with Ventilator

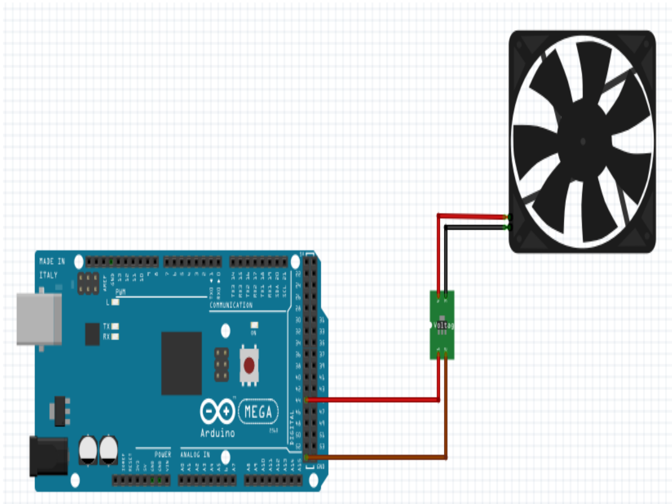

Figure III. 22: Wiring of Arduino with Ventilator

The wiring Arduino with SD card

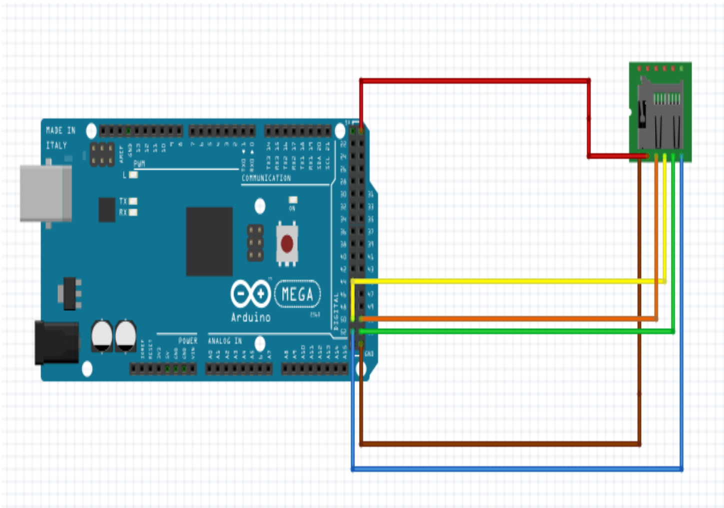

Figure III. 23: Wiring of Arduino with SD card

The overall assembly (by Proteus 8 Professional)

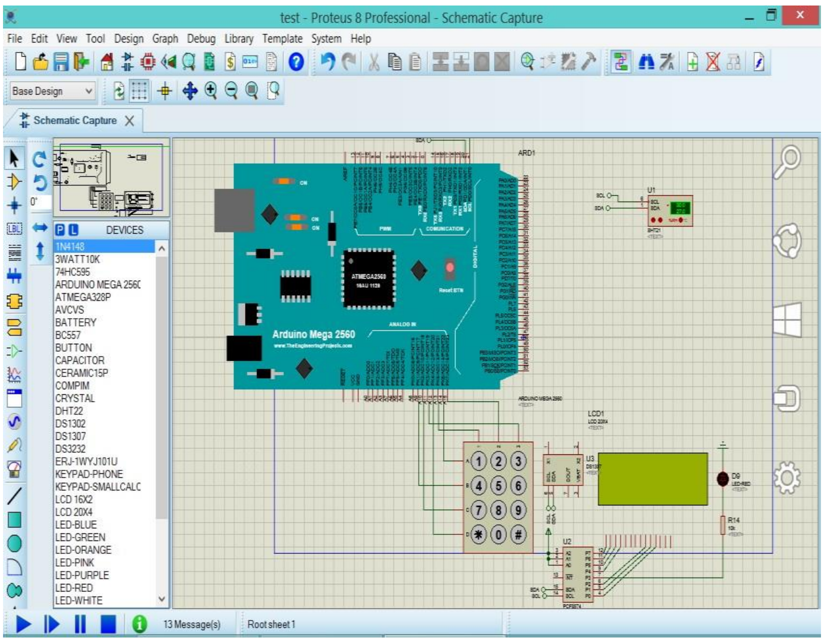

Figure III. 24: Circuit diagram of simulation (proteus)

III.3. Laboratory Instruments:

III.3.1 KERN PCB 3500-2 Balance: 3500g:

This is a measurement device used to track mass while drying.

Figure III. 25: KERN PCB 3500-2 Balance: 3500g

III.3.2. Measurement of water content

The determination of the water content was carried out as follows: in a previously dried and tarred becher, 2-4 grams of samples are introduced for 24 hours at 105 °C, then the set is put to cool in a dryer for 20 minutes, then weighed on a KERN ABT 220-4M Balance: 220g/0,1mg.

KERNABT2204M200 g/0.Balance	KERNABT2204M200 g/0.Balance	Desiccator

Figure III. 26: Materials used to determine the initial water content

III.3.3. Plant-based materials

- ✓ **The Mint**

The mint was supplied by a farm in Mtlili, located 40 km south of Ghardaia.

The initial water content of mint was 4,543 kg H2O/kg dB (hydrated base at 77.99%).

Figure III. 27: The Mint

✓ The Parsley

The Parsley was supplied by a farm in Mtlili, located 40 km south of Ghardaia.

The initial water content of Persil was 4.234kg H_2O/kg dB (hydrated base at 70%).

Figure III. 28: The Parsley

✓ Henna

The Henna was supplied by a farm in Mtlili, located 40 km south of Ghardaia.

The initial water content of henna was kg H_2O/kg dB (hydrated base at 80 %).

Figure III. 29: Henna

III.4. Drying protocol

In this study, we investigated the drying kinetics of mint, **Parsley**, and henna leaves under varying weather conditions in a semi-arid climate. A single greenhouse-type solar dryer was used to carry out a series of drying experiments, aiming to preserve the specific properties of these leaves. The solar dryer utilized solar energy to generate heat, creating a controlled and efficient drying environment for moisture removal. Monitoring and analysis of the drying kinetics of mint, Parsley and henna leaves allowed us to understand the impact of changing weather conditions on the drying process. Additionally, we determined the initial moisture content of mint, Parsley and henna by subjecting samples weighing 3 to 5 g, placed in aluminum dishes (total of 5 dishes), to a temperature of 105 °C for 24 hours to achieve maximum dryness. To determine the drying kinetics, we followed the protocol described in (Figure III-30).

Figure III. 30: Stage Preparation of the sample parsley

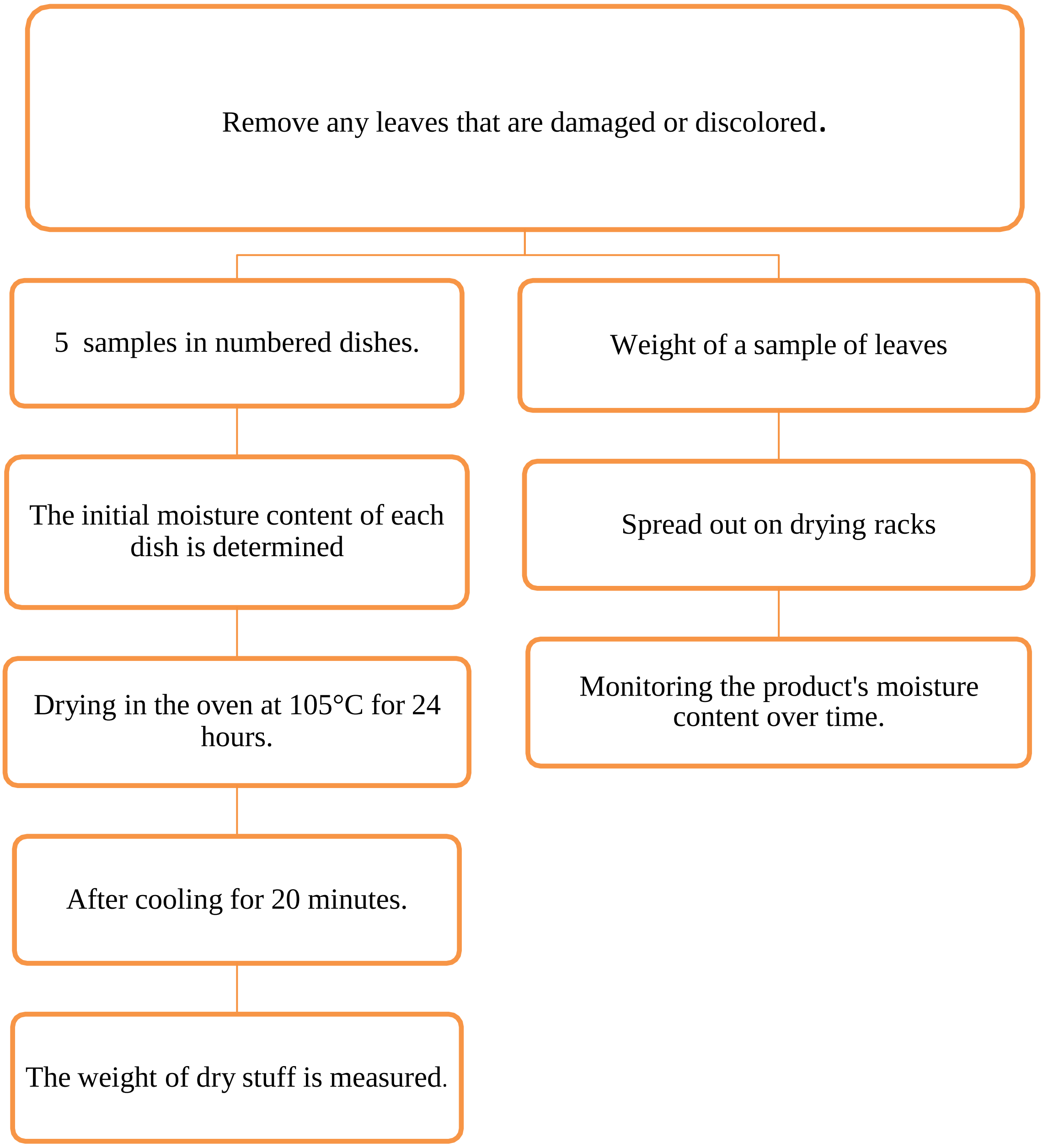

Figure III. 31: Schematic diagram of the drying process (Mint. Parsley Henna).

III.4.1. Characteristic square curve

To monitor and quantify the progressive decrease in its average absolute humidity (M), the simplest method is to weigh the product during drying. The humidity rate is defined by the ratio between the water mass contained in the product at a given moment (t) and the mass (MH) of the completely dry product. This mass **(MS)** can only be achieved if the drying air is completely devoid of moisture. The absolute humidity of the product varies from the initial value M0 to the final balance value **(ME)**, which depends on the air drying conditions. Drying curves illustrate variations in humidity ratio **M(t) = (MH - MS) / MS** depending on time. The equilibrium state is reached at a constant drying temperature when, during two consecutive weighings, the mass of the product remains identical. To determine the dry mass of the product **(MS)**, the product is dried in a solar dryer and then placed in a case set at 105°C for 24 hours until it reaches its maximum dehydration.

III.4.2. Drying kinetics modeling

The challenge in modeling solar drying curves is often to create a function that validates the equation below: **MR=f(t)**

$$MR(t) = \frac{M(t)\text{-}Me(t)}{M0(t) - Me(t)} \tag{11}$$

With M(t) Me(t) and M0(t) are the values of the water content (dry base) at the moment t, at the infinite (balance) and at t=0, respectively. 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 drying curves. The equations of these models express the evolution of the reduced MR water content over time. These formulas contain constants that are adjusted to match the theoretical results with the experimental drying curves. Therefore, they are valid only in the experimental research area for which they were established.

Table III. 9: Mathematical models of solar drying in thin layers

N°	*Modelés*	*Equations*	*Références*
01	*Newton (Lewis, Exponential, single exponential) model*	*MR = exp(-kt)*	*[lewis, 1921]*
02	*Page Model*	*MR = exp(-kt^{n})*	*[xanthopoulos et al., 2002]*
03	*Modified page model*	*MR = exp(-kt^{n})*	*[midilli et al., 2002]*
04	*Henderson and pabis(single term,generalizd exponential)Model*	*MR = aexp(-kt)*	*[zhang etal., 2002]*
05	*Logarithmic (Asymptotic,yagciogluet al.)Model*	*MR = aexp(-kt)+b*	*[yaldiz et al.,2002]*
06	*Midilli-Kucuk (Midilli, Midilli etal.) Model*	*MR = aexp(-kt^{n})+bt*	*[midilli et al., 2002]*
07	*Approximation of Diffusion (Diffision Approach) Model*	*MR= aexp(-kt) +(1-a)exp(kbt)*	*[yaldiz et al., 2001]*

The author's seven different models, which are listed in Table III.1-1, will be compared to determine which one is the most suited. The "Origine Pro 8.0" program was used to run regression analysis. One of the key considerations in choosing the ideal model for determining the drying curves was the coefficient (R2) **(Balbay et al., 2012).** In addition to(R2), different statistical parameters such as the reduced square khi (χ2) and the square root of the average square error (RMSE) were used to determine the quality of the adjustment. These coefficients can be calculated as follows **(Naderinezhad et al., 2016; Ruhanian et al, 2016):**

$$R^2 = 1 - \frac{\sum_{i=1}^{N} (MRexp\,, i - MRpr\, é, i)2}{\sum_{i=1}^{N} (MRexp - MRpr\,, i)2} \quad (12)$$

$$\chi^2 = \frac{\sum_{i=1}^{N} (\mathrm{MRexp}\,, \mathrm{i} - \mathrm{MRpr}\, é, \mathrm{i})2}{N - n} \quad (13)$$

$$RMSE = \sqrt{\frac{1}{N} + \sum_{i=1}^{N} (MRexp\,, i - MRp_r\, é, i)2} \quad (14)$$

With:

$$\mathrm{MRexp} = \frac{\sum_{i=1}^{N} \mathrm{MRexp}\,, \mathrm{i}}{N} \quad (15)$$

Where MRexp and MRpr e are, respectively, the water content resulting from the experiment and predicted by the model, N is the number of observations, n is the amount of constants in the model.

Statistical and correlation analysis and regression methods are widely used in the modeling of the drying behavior of various agricultural products. Linear and non-linear regression models are essential to establishing a relationship between variables and are of paramount importance in cases where the authors have not established empirical relationships.

III.4.3. Determination of the actual diffusiveness of water

The effective diffusion coefficient and the concentration gradient of the water content determine the mass transfer rate through pure diffusion. Therefore, it is crucial to determine this later coefficient in order to more accurately describe mass transfer using the related Fick law, whose equation is shown in **(Vasi et al., 2016):**

$$\partial MR/\partial t = ❑(Deff\, ❑MR) \quad (16)$$

Assuming that Deff's value is constant, it is possible to obtain:

$$\partial MR/\partial t = Deff\, ❑^2 MR \quad (17)$$

The slice of dried product can be regarded as a uniform plate subjected to a non-stagnant gradual diet with a uniform initial distribution and equal surface concentrations. Assuming that the matrix is an infinite, non-deformable plate.

(negligible or extended retractable) with a uniform distribution of initial moisture, negligible external resistance and constant diffusiveness, the analytical solution of Fick's second law was developed by Crank **(Crank, 1975):**

$$\mathrm{MR} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp(-(2n+1)^2\pi^2 D_{eff} t/4L^2) \tag{18}$$

Where: Deff is the actual diffusiveness (in m2/s), t is the time (in s), L is half of the thickness of the slice (in m) and n is a positive integer.

For a sufficiently long processing time, all terms in the next sequence (n≥1) were considered negligible compared to the first term. So the equation can be assumed as follows:

$$MR = \frac{8}{\pi^2}\, exp(-\pi^2 D_{eff} t/4L^2) \tag{19}$$

The equation can be rearranged and expressed as follows:

$$Ln(MR) = Ln\,(\frac{8}{\pi^2}) - \pi^2 D_{eff} t/4L^2 \tag{20}$$

Values of experimental drying data are expressed as ln (MR) depending on the rehydration time at various temperatures. This is how the effective diffusiveness is determined:

$$Slope(k) = -\pi^2 D_{eff}/4L^2 \tag{21}$$

Bibliography

« J»

- J. Crank. *The Mathematics of Diffusion*. Oxford science publications. Clarendon Press, 1979. ISBN 9780198534112. URL https://books.google.fr/books?id= eHANhZwVouYC

« M»

- M.Vasi ˇ c, Zagorka Radojevi ´ c, and Robert Rekecki. Mathematical modeling of isother- ´mal drying and its potential application in the design of the industrial drying regimes of clay products. In Kuodi Jian, editor, *Operations Research*, chapter 5. IntechOpen, Rijeka, 2016. doi : 10.5772/64983. URL https://doi.org/10.5772/64983.

Chapter IV

Results and Discussion

VI.1. Results and Discussions

Experiments were conducted at the experimental stand of the Unit of Applied Research for Renewable Energies (URAER) in Ghardaia (Fig. IV.1), located at latitude 32.37°N and longitude 3.77E, to observe the thermal behavior of a solar dryer modeled over the course of one day under real operating conditions. The drying properties of henna, parsley, and mint were studied over three consecutive days. The thermal performance of the solar dryer model was measured in terms of system efficiency, constant temperature, and absorber. The temperature inside the dryer was maintained at a constant 50 degrees Celsius. Figures 5 to 10 show photographic views of fresh and sun-dried product samples, as well as prototypes of solar dryers.

Figure IV. 1: Photograph of the experiment platform in URAER.

IV.1. Performance of the solar dryer prototype without products

IV.1.1 Validation tests

In our experiment, we decided to focus on a specific type of solar dryer, with the primary goal of achieving temperature stability inside the dryer regardless of external weather conditions. We worked on developing the design to enable the dryer to maintain a constant temperature at the desired value for an extended period. The efforts were concentrated on improving the control system and thermal insulation of the dryer.

After conducting the experiments, it became evident that the new dryer design effectively achieved our desired goal. It successfully maintained a constant temperature inside the dryer continuously, even in the presence of varying external weather conditions. Additionally, we observed that the performance of the dryer was positively influenced by the improvements we made in the control system. This is shown in the following curves:

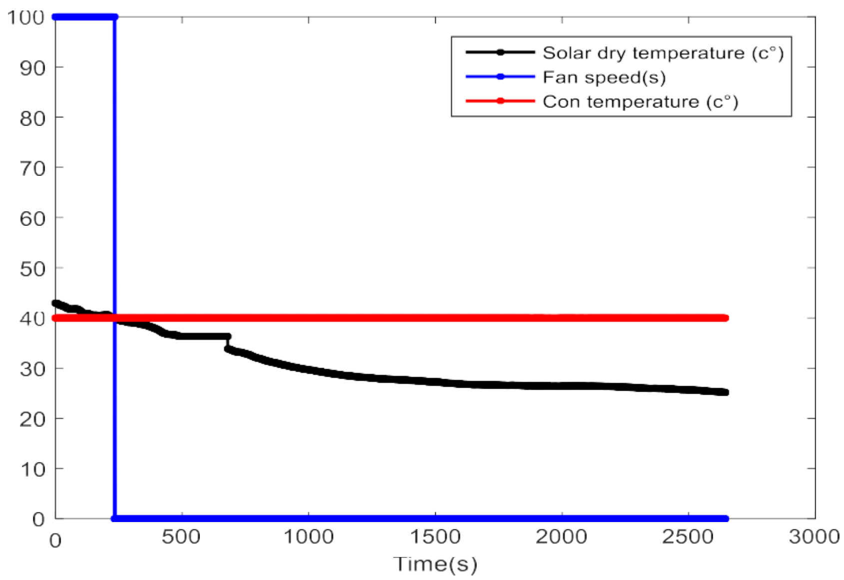

Figure IV. 2: The time evolution of the dryer temperature for 06/04/2023.

Figure IV. 2 presented curve delineates the temporal evolution of the dryer's temperature. Commencing at an initial value of 43 degrees Celsius, the temperature exceeded the designated set point of 40 degrees Celsius. Concurrently, the fan was operating at its maximum capacity, contributing to enhanced heat dissipation. Subsequently, the temperature exhibited a decliningtrend, receding to 25 degrees Celsius. During this phase, the fan was deactivated.

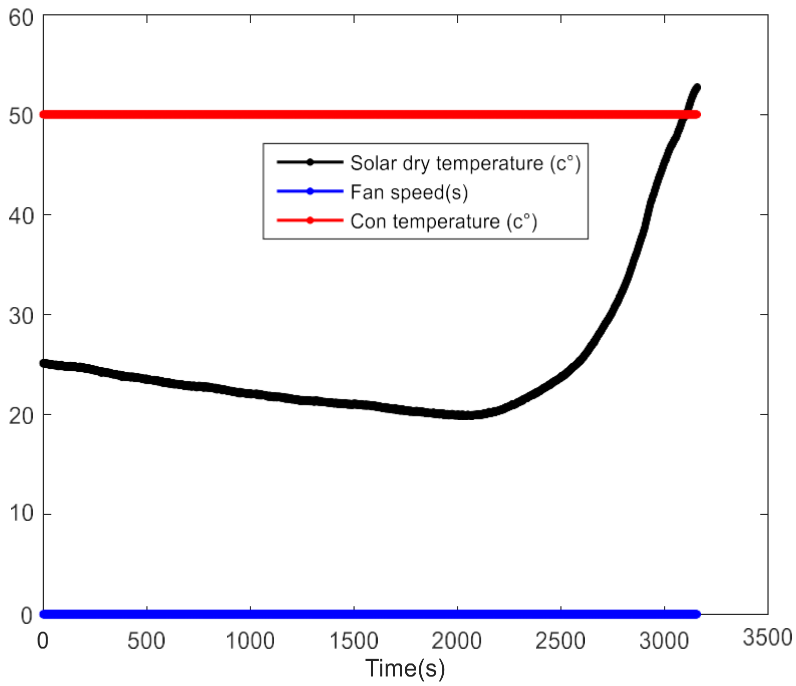

Figure IV. 3: The time evolution of the dryer temperature for 06/05/2023.

The Figure IV. 3 graphically represents the dryer's temperature. The dryer's temperature was initially measured at 25 degrees Celsius, then progressively rose to a level just below 50 degrees Celsius. The dryer's designated working temperature is 50 degrees Celsius. Notably, the fan speed was kept 0, suggesting that the fan was not operating, during this time.

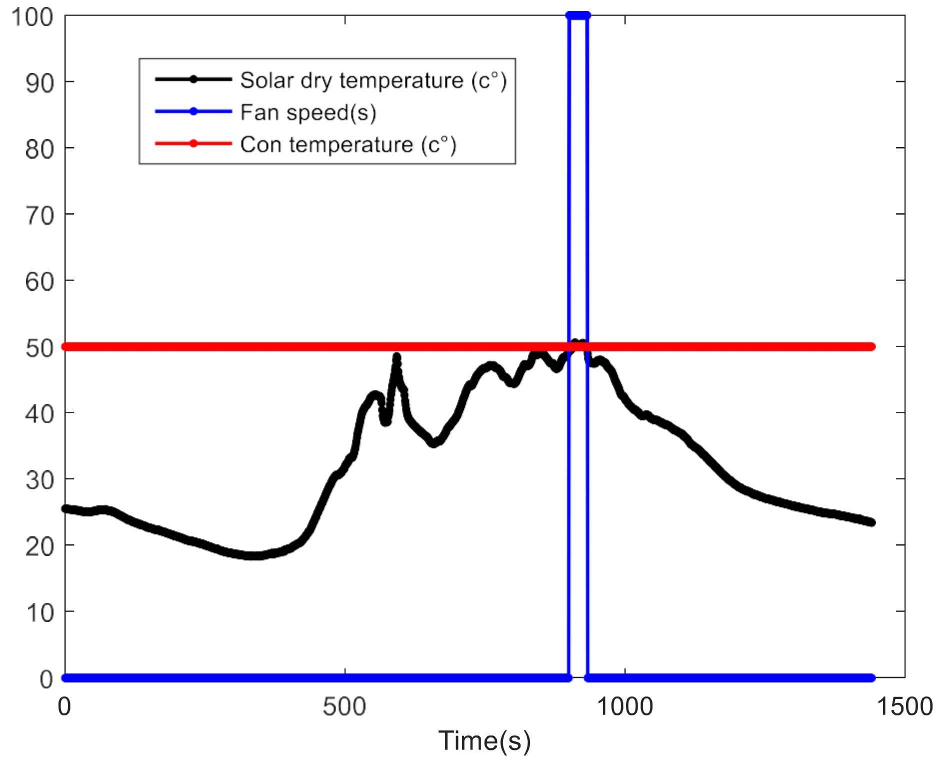

Figure IV. 4: The time evolution of the dryer temperature for 06/06/2023.

The Figure IV. 4 deftly depicts the dryer's thermal dynamics throughout time. The dryer's initial temperature was 25 degrees Celsius, far lower than the 50 degrees Celsius listed as the fixed setting. The fan was not operating during this time, which resulted in little heat dissipation. The temperature then progressively increased, though it continued to be below therequired 50 degrees Celsius threshold. The fan was activated as a result of the temperature increase, running at full speed and producing efficient thermal control. The graph shows a decrease in temperature after the fan-assisted temperature control, eventually settling at 30 degrees Celsius. This decrease denotes the end of fan operation.

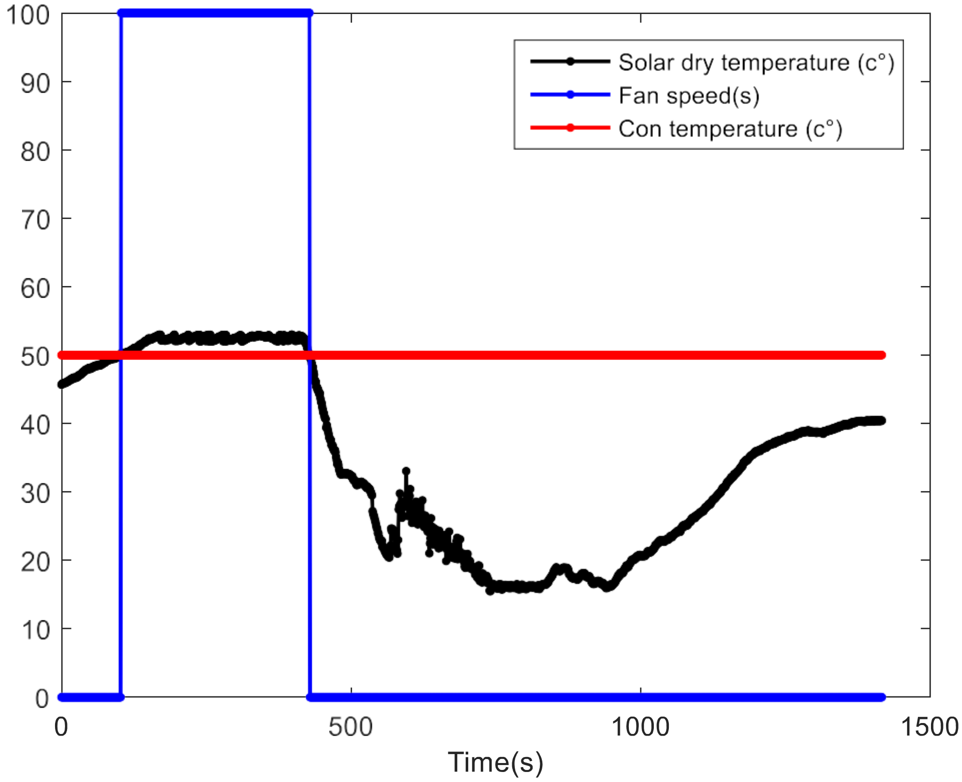

Figure IV. 5: The time evolution of the dryer temperature for 06/07/2023.

The Figure IV. 5 illustrated curve provides a comprehensive visualization of the temporal evolution of the dryer's temperature under varying operational conditions. Initially, the temperature of the dryer was logged at 48 degrees Celsius, slightly below the designated set temperature of 50 degrees Celsius. This phase was characterized by the absence of fan activity, , leading to limited heat dissipation. As time progressed, the temperature exhibited an upward trajectory, peaking at 52 degrees Celsius. This marked temperature elevation triggered the activation of the fan, operating at its maximum capacity with. The fan's involvement facilitated effective thermal management within the dryer. Subsequent to the fan-assisted cooling phase.

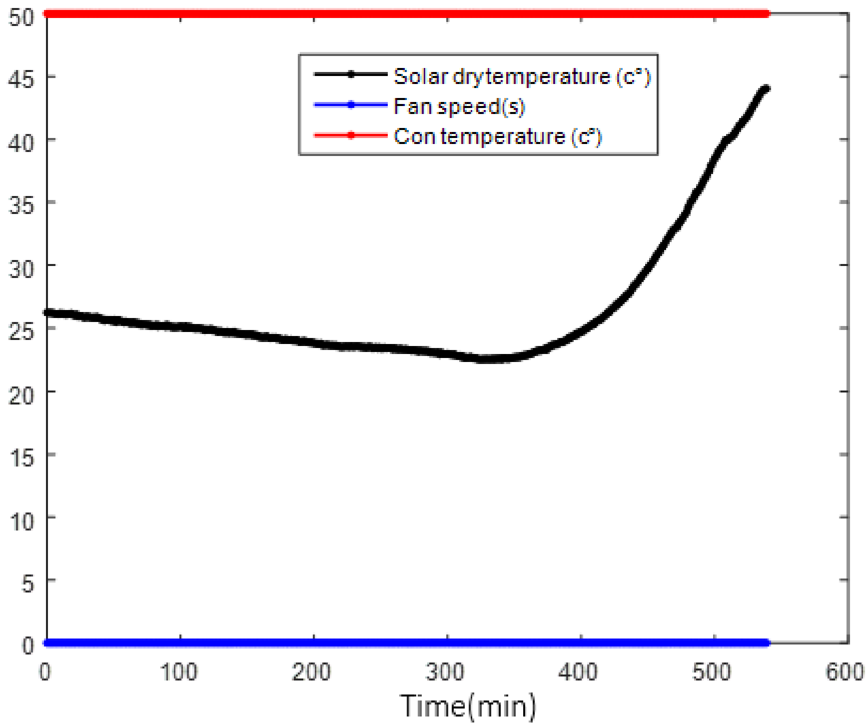

Figure IV. 6: The time evolution of the dryer temperature for 06/08/2023.

The dynamic thermal behavior of the dryer over a given time period is described by the fifth shown Figure IV. 6. The dryer's temperature began to rise gradually from its initial readingof 27 degrees Celsius to a maximum of 44 degrees Celsius, which is still below the recommended set temperature of 50 degrees Celsius. The fan wasn't working at this period.

IV.2. Dryer henna, mint and parsley in a new direct solar dryer

IV.2.1. Dry mint in a day (06/06/23)

We dried a 4-gram sample of mint using a direct solar dryer. **Figure IV.7** shows the drying characteristics of mint in terms of moisture content over time.

By observing the drying curve, two distinct drying periods can be distinguished. The first period is characterized by a rapid decrease in moisture content, while the second period shows a slower decrease in moisture content until the end of the drying process. Moisture content was determined regularly over the course of drying hours in order to accurately monitor changes.

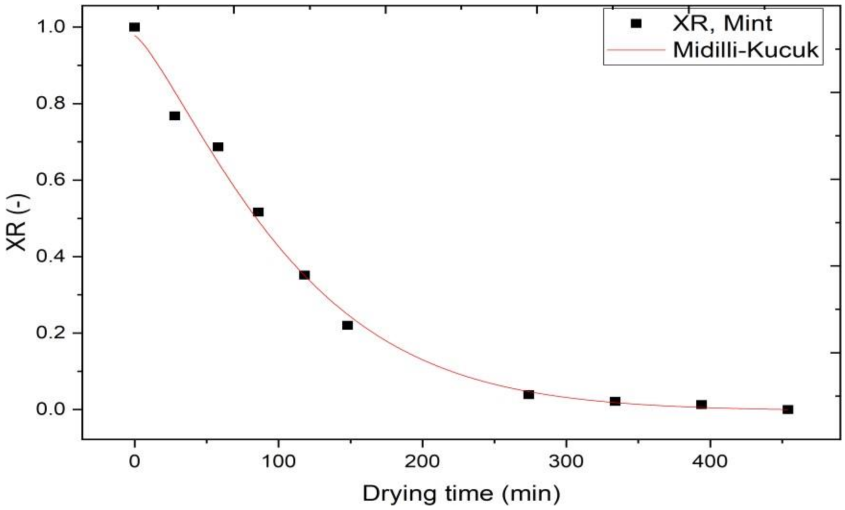

Figure IV. 7: Variation of water content with time in direct solar dryer (the mint).

Figure IV. 8: Sample after drying.

IV.2.1.1. Empirical modeling of mint thin-layer drying process

Table IV .1. Summarizes the statistical results obtained from the regression analysis of the air-drying process in the DIRECT solar dryer. The relevance of various models was assessed on the basis of their correlation coefficients **"R2",** their reduced values of chi square **"χ2"** and their average square errors **"RMSE".** The model with the highest **"R2"** coefficient and the lowest values of "**χ2"** and "**RMSE"** was identified as the best representation of **the mint** drying process in this prototype. Analysis of **XR** data for air drying revealed that the **Midilli-Kucuk** model showed the highest **"R2"** coefficient as well as the lowest values of "**χ2**" and RMSE. Therefore, the **Midilli-Kucuk** model demonstrated the best agreement between experimental and predicted moisture levels, optimally adjusting to experimental data. Thus, the **Midilli-Kucuk** model turns out to be the most appropriate choice for **mint** drying in Protototypes in Direct Solar Drying. These results corroborate the research conducted by:

Table IV. 1: Statistical results obtained

Model	**Constants**				**R^2**	**RMSE**	***X^2***
	K	**n**	**a**	**b**			
Newton	0.00877				0.98589	0.04327	0.00187
Page	0.00297	1.23049			0.99316	0.03195	0.00102
Modified Page	0.00884	1.2358			0.99316	0.03194	0.00102
Henderson and Pabis	0.00903		1.02541		0.98671	0.04454	0.00198
Logarithmic	0.00807		1.06107	-0.04753	0.99014	0.04101	0.00168
Midilli-Kucuk	0.00232	1.2759	0.97781	0.84033E-6	0.99368	0.03547	0.00126
Approximationofdiffusion	0.00807		1.06108	7.18484	0.99014	0.04101	0.00168

IV.2.2. Dry henna in a day (06/05/23)

We used a direct solar dryer to dry a 4-gram sample of **Henna**. The drying characteristics of **Henna** in terms of moisture content are depicted over time in **Figure IV.09**. Two distinct drying periods can be determined by looking at the drying curve. While the second period exhibits a slower decline in moisture content until the drying process is complete, the first period is characterized by a quick fall in moisture content. In order to precisely track changes throughout drying hours, moisture content was periodically monitored.

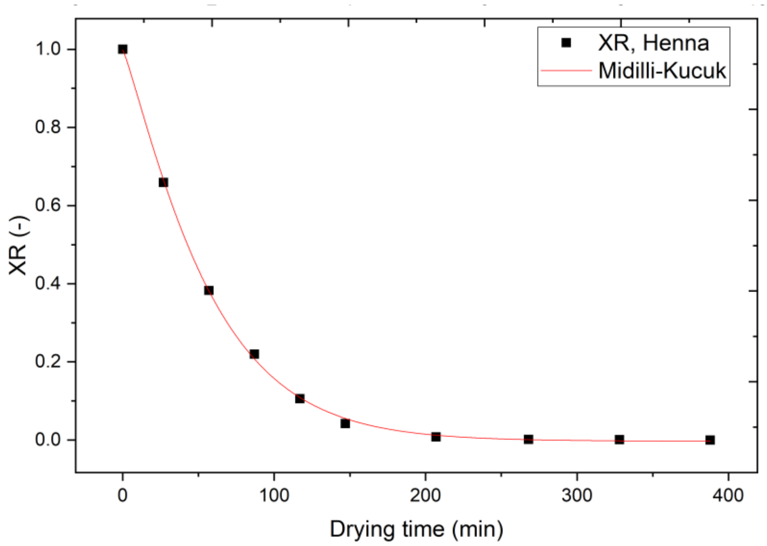

Figure IV. 9: Variation of water content with time in direct solar dryer.

Figure IV. 10: Sample afterdrying.

IV.2.2.1. Empirical modeling of Henna thin-layer drying process

Table IV .2. Summarizes the statistical results obtained from the regression analysis of the air-drying process in the DIRECT solar dryer. The relevance of various models was assessed on the basis of their correlation coefficients **"R2",** their reduced values of chi square **"χ2"** and their average square errors **"RMSE".** The model with the highest **"R2"** coefficient and the lowest values of "**χ2"** and "**RMSE"** was identified as the best representation of **Henna** drying process in this prototype. Analysis of **XR** data for air drying revealed that the **Midilli-Kucuk** model showed the highest **"R2"** coefficient as well as the lowest values of "**χ2**" and RMSE. Therefore, the **Midilli-Kucuk** model demonstrated the best agreement between experimental and predicted moisture levels, optimally adjusting to experimental data. Thus, the **Midilli-Kucuk** model turns out to be the most appropriate choice for **Henna** drying in Protototypes in Direct Solar Drying. These results corroborate

the research conducted by:

Table IV. 2: Statistical results obtained from different thin-layer Henna drying models.

Model	**Constants**				**R^2**	**RMSE**	**X^2**
	K	**n**	**a**	**b**			
Newton	0.01747				0.99657	0.02007	4.02758E-4
Page	0.00903	1.15588			0.99959	0.00738	5.44859E-5
Modified Page	0.01703	1.15672			0.99959	0.00738	5.4473E-5
Henderson and Pabis	0.01774		1.01738		0.99691	0.0202	4.08212E-4
Logarithmic	0.01704		1.0296	-0.0154	0.99772	0.01853	3.43519E-4
Midilli-Kucuk	0.00906	1.15411	0.99844	-8.12212E-6	0.99961	0.00827	6.83294E-5
Approximation of diffusion	0.01704		8.84228	2574.22087	0.99772	0.01853	3.43519E-4

IV.2.3. Dry Parsley in a day (05/06/23)

We used a direct solar dryer to dry a 4-gram sample of **Parsley**. The drying characteristics of **Parsley** in terms of moisture content are depicted over time in **Figure IV.11**. Two distinct drying periods can be determined by looking at the drying curve. While the second period exhibits a slower decline in moisture content until the drying process is complete, the first period is characterized by a quick fall in moisture content. In order to precisely track changes throughout drying hours, moisture content was periodically monitored.

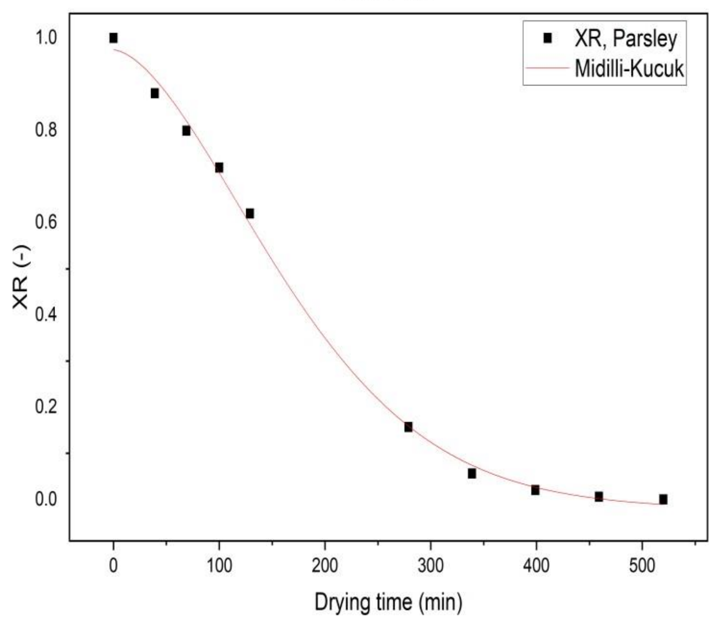

Figure IV. 11: Variation of water content with time in direct solar dryer.

Figure IV. 12: Sample after drying.

IV.2.3.1. Empirical modeling of Parsley thin-layer drying process

Table IV .3. summarizes the statistical results obtained from the regression analysis of the air-drying process in the DIRECT solar dryer. The relevance of various models was assessed on the basis of their correlation coefficients **"R2",** their reduced values of chi square **"χ2"** and their average square errors **"RMSE".** The model with the highest **"R2"** coefficient and the lowest values of "**χ2"** and "**RMSE"** was identified as the best

representation of **the Parsley** drying process in this prototype. Analysis of **XR** data for air drying revealed that the **Midilli-Kucuk** model showed the highest **"R2"** coefficient as well as the lowest values of "**χ2**" and RMSE. Therefore, the **Midilli-Kucuk** model demonstrated the best agreement between experimental and predicted moisture levels, optimally adjusting to experimental data. Thus, the **Midilli-Kucuk** model turns out to be the most appropriate choice for **Parsley** drying in Protototypes in Direct Solar Drying. These results corroborate the research conducted by

Table IV .3. Statistical results obtained from different thin-layer Parsley drying models.

Model	Constants				R^2	RMSE	X^2
	K	n	a	b			
Newton	0.00525				0.94528	0.09647	0.00931
Page	2.0028E-4	1.62256			0.99677	0.02486	6.17954E-4
Modified Page	0.00526	1.63795			0.99679	0.02479	6.14766E-4
Henderson and Pabis	0.00584		1.10473		0.95857	0.08903	0.00793
Logarithmic	0.00349		1.33716	-0.28234	0.9839	0.05932	0.00352
Midilli-Kucuk	1.42064E-4	1.67307	0.97406	-3.4189E-5	0.99788	0.02325	5.40505E-4
Approximation of diffusion	0.00349		1.33723	11.78741	0.9839	0.05932	0.00352

General conclusion and perspective

General conclusion and perspective

Conclusion:

In conclusion, this master's thesis has delved into the experimental assessment of a novel direct forced convection solar dryer augmented by photovoltaic technology. Through meticulous craftsmanship within the Applied Research Unit in Renewable Energy, we successfully designed and constructed an energy-efficient solar drying system, marked by the integration of a 10-watt photovoltaic panel and a sophisticated control system. Our investigation has yielded several key findings and achievements:

Efficient Drying Performance: Drying experiments conducted on fresh mint, parsley, and henna samples have demonstrated the remarkable efficiency of our solar dryer. We have effectively reduced the initial high moisture content of these samples to their respective target levels within reasonable timeframes, thus showcasing the system's practical utility.

Mathematical Modeling Validation: The adoption of the Midilli-Kucuk model for drying kinetics modeling has proven to be accurate in predicting the drying behavior of the aforementioned samples. This model can serve as a valuable tool for optimizing drying processes in similar solar drying systems.

Control System Efficacy: The control system's real-time adjustment of drying temperatures based on meteorological data, facilitated by the Arduino interface, has been rigorously tested and found to be highly effective. This feature enhances the system's adaptability to fluctuating environmental conditions.

Perspective:

Looking ahead, the outcomes of this research present several promising perspectives for the application and development of solar drying systems assisted by photovoltaic cells:

Sustainable Agriculture: The integration of renewable energy sources, such as photovoltaics, into agricultural practices offers a sustainable means of preserving crops and agricultural products. As the world grapples with climate change and energy sustainability, these systems can significantly contribute to more eco-friendly farming practices.

Customization and Scalability: The success of our solar drying system serves as a foundation for customization and scalability. Tailoring such systems to suit different crops and climatic conditions can optimize drying processes and maximize energy efficiency.

Technological Advancements: The continuous advancement of photovoltaic technology, coupled with improvements in control systems and automation, holds great potential for enhancing the performance and accessibility of solar drying solutions. Future research can explore innovations in these areas to further improve system efficiency and usability.

Economic Viability: Investigating the economic feasibility of implementing solar drying systems in various agricultural settings can provide valuable insights into the cost-effectiveness of these solutions, potentially encouraging broader adoption.

In conclusion, this master's thesis not only underscores the practicality and efficiency of solar drying systems powered by photovoltaic cells but also highlights the potential for sustainable agricultural practices. The integration of renewable energy sources into the agricultural sector represents a promising avenue for addressing food security and environmental challenges in the years to come.