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بسم الله الرحمن الرحيم

شكر و عرفان

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"وَآخِرُ دَعْوَاهُمْ أَنِ الْحَمْدُ لِلَّهِ رَبِّ الْعَالَمِينَ"

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"فَرِحِينَ بِمَا آتَاهُمُ اللَّهُ مِن فَضْلِهِ"

الإهداء

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ABBREVIATION

URAER	Applied Research Unit in Renewable Energies
PCM	Phase Change Material
LTES	Latent Thermal Energy Storage
TES	Thermal Energy Storage
NARX	Nonlinear Auto Regressive with eXogenous input
ANN	Artificial Neural Network
CO_2	Carbon dioxide
Rh	Relative humidity
N-S	North-South
E-W	Est-West
FAO	Food and Agriculture Organization
SHS	Sensible Heat Storage
LHS	Latent Heat Storage
$CaCl_2$	Calicium Chloride
COP	Cofficient Of Performance
RMSE	Root Mean Square Error
MSE	Mean Squared Error

ABSTRACT

The world has witnessed significant demographic growth and environmental challenges, prompting researchers to seek sustainable solutions to ensure food security and protect the environment. To address these challenges, solar energy technologies have been adopted in agricultural greenhouses, which are an important part of modern agriculture. Despite advancements in greenhouse technology, improving the microclimate remains a challenge, as this gap affects agricultural production, increases operational costs, and consumes more energy.

This study aims to improve the heating system in semi-arid regions using a new latent heat storage system, taking ventilation into account to enhance productivity. In this experiment, a phase change material (PCM) was used to store heat during the day and release it at night. To verify the effectiveness of the system, the obtained results were analyzed based on temperature and relative humidity inside the greenhouse.

Additionally, the **NARX (Nonlinear Autoregressive with Exogenous Inputs)** algorithm was employed within the predictive model. This algorithm relies on past values of the studied variables and external inputs, allowing for capturing the precise temporal dynamics of the microclimate inside the greenhouse. The results showed that this approach improves prediction accuracy and supports better decision-making in agricultural energy management.

Key words : Greenhouses, heating system, phase change material(PCM), temperature, solar energy , , the **NARX** algorithm .

الملخص

شهد العالم نمواً ديمغرافياً كبيراً وتحديات بيئية، مما دفع الباحثين إلى اللجوء إلى حلول مستدامة لضمان الأمن الغذائي والحفاظ على البيئة. ولمواجهة هذه التحديات، تم تبني تقنيات الطاقة الشمسية في الدفيئات الزراعية، التي تُعد جزءاً مهماً في الزراعة الحديثة. وعلى الرغم من تطور تكنولوجيا الدفيئات، فإن تحسين المناخ المصغر (الميكرومناخ) لا يزال يمثل تحدياً، حيث تؤثر هذه الفجوة على الإنتاج الزراعي، وتزيد من التكاليف التشغيلية، وتستهلك المزيد من الطاقة **.**تهدف هذه الدراسة إلى تحسين نظام التدفئة في المناطق الشبه جافة باستخدام نظام جديد لتخزين الطاقة الحرارية الكامنة، مع الأخذ بعين الاعتبار التهوية، بهدف تعزيز الإنتاجية. في هذه التجربة، تم استخدام مادة متغيرة الطور **(PCM)** لتخزين الحرارة خلال النهار وإطلاقها ليلاً. وللتحقق من فعالية النظام، تم تحليل النتائج المتحصل عليها بناءً على درجات الحرارة والرطوبة النسبية داخل الدفيئة **.**

بالإضافة إلى ذلك، تم اعتماد خوارزمية **NARX (Nonlinear Autoregressive with Exogenous Inputs)** ضمن النموذج التنبؤي، حيث تعتمد هذه الخوارزمية على القيم السابقة للمتغيرات المدروسة والمدخلات الخارجية، مما يسمح بالتقاط الديناميكية الزمنية الدقيقة للمناخ داخل الدفيئة. وأظهرت النتائج أن هذا النهج يعزز دقة التنبؤ ويدعم اتخاذ قرارات أفضل في إدارة الطاقة الزراعية**.**

الكلمات المفتاحية: البيوت البلاستيكية، نظام التدفئة، مادة متغيرة الطور، درجة الحرارة، الطاقة الشمسية ، خوارزمية

NARX

RESUMER

Le monde a connu une croissance démographique importante ainsi que des défis environnementaux, ce qui a poussé les chercheurs à rechercher des solutions durables pour garantir la sécurité alimentaire et protéger l'environnement. Pour relever ces défis, les technologies d'énergie solaire ont été adoptées dans les serres agricoles, qui constituent une partie importante de l'agriculture moderne. Malgré les avancées dans la technologie des serres, l'amélioration du microclimat demeure un défi, car cette lacune affecte la production agricole, augmente les coûts opérationnels et consomme davantage d'énergie.

Cette étude vise à améliorer le système de chauffage dans les régions semi-arides en utilisant un nouveau système de stockage de chaleur latente, en tenant compte de la ventilation afin d'accroître la productivité. Dans cette expérience, un matériau à changement de phase (PCM) a été utilisé pour stocker la chaleur pendant la journée et la libérer la nuit. Pour vérifier l'efficacité du système, les résultats obtenus ont été analysés en fonction de la température et de l'humidité relative à l'intérieur de la serre.

De plus, l'algorithme NARX (Nonlinear Autoregressive with Exogenous Inputs) a été adopté dans le modèle prédictif. Cet algorithme s'appuie sur les valeurs passées des variables étudiées ainsi que sur des entrées externes, ce qui permet de capturer la dynamique temporelle précise du microclimat à l'intérieur de la serre. Les résultats ont montré que cette approche améliore la précision des prédictions et soutient une meilleure prise de décision dans la gestion énergétique agricole.

Mots-clés: Serres, système de chauffage, matériau à changement de phase(MCP), température, énergie solaire , l'algorithme NARX .

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General introduction

General introduction

Food is one of the basic necessities for sustaining life, alongside air and water. With the current rapid population growth, the world's population is expected to reach approximately 9.6 billion by 2050, leading to a significant increase in the demand for food resources. In light of these challenges, agriculture has become a fundamental pillar for achieving food security, which has driven the introduction of modern technologies in this sector to improve production, ensure sustainability, and address various environmental and economic crises.

Among the most important of these technologies is the use of plastic greenhouses as an effective means of controlling the climatic factors that affect crop growth, such as temperature, humidity, sunlight, and carbon dioxide concentration. These greenhouses also allow for the production of crops outside their natural seasons, making them vital plant production factories that operate year-round [1][2].

The concept of greenhouses dates back to ancient times, where primitive materials were used to protect crops [3]. However, this idea evolved over time. Glass greenhouses began appearing in the 17th century in Europe to grow plants that could not adapt to the local climate, though their high cost limited their widespread use. By the mid-20th century, researchers turned to transparent plastic materials, particularly polyethylene, to reduce costs and simplify installation and maintenance. This led to the broader spread of plastic greenhouses and a rise in agricultural production.

Despite these advantages, plastic greenhouses still face specific challenges, particularly in hot climates, with regard to heating during cold seasons and controlling the internal microclimate. This has led to the need for innovative solutions to improve the efficiency of these systems. One of the most prominent solutions is the use of Phase Change Materials (PCMs), which have the ability to store thermal energy and release it when needed during phase transitions, relying on solar energy, thus contributing to environmental conservation and supporting sustainable agriculture.

In Algeria, desert agriculture has undergone a significant transformation, shifting from traditional farming to intensive, market-oriented agriculture. With the expansion of cultivated land, farmers faced challenges related to costs and resource scarcity. However, technological advancements have enabled better control over the local microclimate, with greater reliance on solar energy as an ideal solution for sustainable agriculture in these regions.

In this context, this thesis focuses on improving a solar-powered plastic greenhouse model equipped with a thermal energy storage unit using Phase Change Materials (PCMs), specifically applied in the Ghardaïa region at the Applied Research Unit in Renewable Energies (URAER). The collected results were analyzed to evaluate the effectiveness of this emerging technology in enhancing greenhouse performance.

To further enhance the system's ability to control the internal climate, particularly temperature, an artificial intelligence model based on a NARX (Nonlinear AutoRegressive with eXogenous inputs) neural network was also utilized. This type of network is known for its strong ability to predict complex time series. It was trained using real climatic data (such as external temperature, solar radiation, humidity, and wind speed) in order to accurately forecast future temperatures inside the greenhouse. This facilitates intelligent and efficient control decisions that contribute to improving productivity and reducing resource consumption[4].

Accordingly, the chapters of this thesis will be presented in the following order :

Chapter I: Greenhouse generalities .

- History and Types of Greenhouses.
- How to Control Climatic Factors Inside a Greenhouse .
- Overview of PCMs .

Chapter II: literature review .

- Review of Previous Work on the Development and Optimization of Greenhouses .

Chapter III: Material and Methods .

- Description of the Experimental Site .
- Preparation Method of the Phase Change Material (PCM) Used in the Heating System.
- Detailed Description of the Experimental Greenhouse and the Tools Used for Data collection .
- Explanation of the NARX Neural Network Method for Temperature Prediction **.**

Chapter IV : Results and discussion.

- Analysis and Discussion of the Obtained Data .
- Comparison of Experimental Results with Predicted Results Using the NARX Algorithm .

Chapter I:Generality of greenhouse

I.1. Introduction

Greenhouses are one of the modern agricultural techniques introduced as an alternative to traditional farming. They represent a type of protected agriculture that provides farmers with the opportunity to cultivate crops and achieve high profits. In addition, they contribute to the availability of vegetables and fruits throughout the year, even outside their natural growing seasons.

The success of this type of agriculture depends on precise control of the internal climate of the greenhouse, as well as factors such as the greenhouse's design: its size, height, ventilation openings, wind direction, and the properties of the covering materials.

These greenhouses have provided solutions in the agricultural sector to address the challenges of increasing population density, meet the needs of the population, and achieve sustainability [5].

I.2. Solar energy

Solar energy is a renewable energy source derived from the sun and is considered a green, non-polluting energy (with minimal carbon dioxide emissions). It is harnessed for beneficial purposes, such as enhancing the performance of greenhouses by providing heat, electricity, lighting, and irrigation systems. This contributes to improving agricultural productivity and reducing costs, making it an ideal choice for farmers.

I.3. Definition of greenhouse

A greenhouse is a structure made of various materials, often enclosed in a tunnel-like shape or partially open. It is constructed from transparent materials, such as glass or plastic, that allow sunlight to pass through, supported by frames made of iron. Thanks to its design, it can create a suitable environment to enhance crop growth, ensuring optimal quality and higher productivity, even under unfavorable external conditions [6].

I.4. History of greenhouses

China: The first use of greenhouses dates back to the Qin and Song dynasties, with the development of techniques for storing and preserving the freshness of crops like lychees.

Rome: The beginning of protected agriculture using mica to accelerate the ripening of cucumbers.

France and Europe: In the 17th and 18th centuries, the spread of glass greenhouses to improve early vegetable production.

Netherlands: Leadership in building multi-span glass greenhouses, with advanced environmental control systems.

United States: Rapid development in the 19th century using glass and steel structures.

Japan: The introduction of modern greenhouses in the 19th century to accelerate the cultivation of fruits and vegetables [7].

In Algeria,plastic greenhouses were first introduced between 1969 and 1970 through a project led by the Food and Agriculture Organization. Since then, plastic agriculture has gradually developed ,especially in the **Ghardaïa region**,where expanding greenhouse farming and increasing areas allocated to fruit trees are priorities for agricultural development**.**

In this region, the action plan highlights the development of market horticulture in greenhouses and increasing areas designated for fruit trees as key objectives to stimulate the agricultural sector [8].

I.5. Impact of greenhouses on agriculture

I.5.1. Increase in production and water conservation

Greenhouse agricultural production outperforms open-field agriculture in terms of both quality and quantity. Greenhouses assist with innovative irrigation systems that limit water waste and evaporation, and the plastic coverings also help concentrate evaporated water droplets to reuse them, while protecting the soil from flooding and dust storms.

I.5.2. Protection of plants against climate fluctuations

Greenhouses shield plants from meteorological disturbances such as high winds and cold. These constructions are built of glass or heavy-duty plastic treated with polycarbonate , which can survive strong rains and temperature variations all year. Greenhouses also provide a stable and warm climate in which to produce off-season vegetables like tomatoes and peppers throughout the winter. In addition to their ability to provide a range of fresh vegetables and fruits throughout their growing season, they also offer fresh flowers throughout the year [9] .

I.6. Classification of greenhouse

Greenhouses can be classified based on various factors such as location, external climate, the type of plants cultivated, and their environmental requirements. The most common types include [8]:

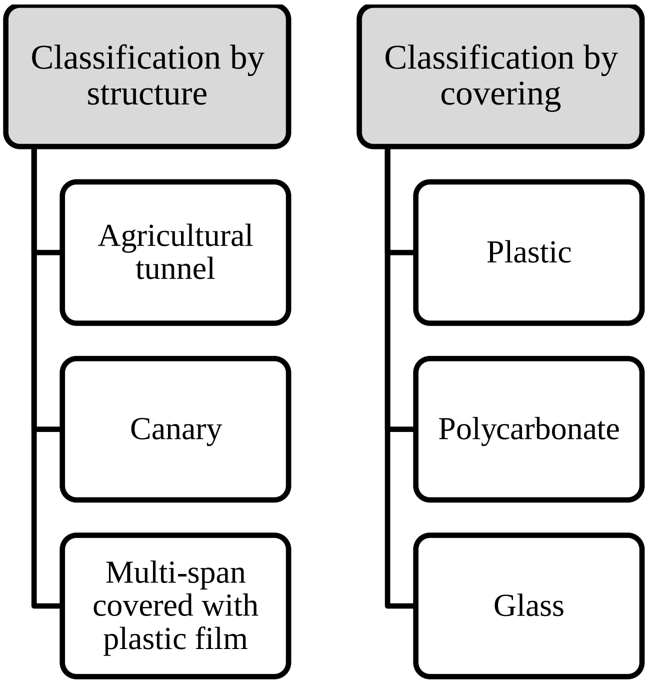


Figure I.1 Classification of greenhouse

I.6.1. Classification by structure

I.6.1.1. Agricultural tunnel

Its design is simple and cost-effective, suitable for small farms. It is usually covered with plastic, and it is easy to assemble and dismantle .

Figure I.2 Agricultural Tunnel [10]

I.6.1.2.Canary

Its height ranges between 3-4 meters (5-6 meters for the improved version), and its dimensions vary depending on the area it covers, reaching several hectares due to its resistance to weather fluctuations and stability over a long period [10].

Figure I.3 Canary greenhouse

I.6.1.3. Multi-span

These greenhouses are characterized by having openings for ventilating the crops and improving their quality by regulating the temperature and humidity inside. This type is used in commercial farming, especially in areas that experience climatic fluctuations (which is the type we conducted our experiment on) [10].

Figure I.4 Multi-span covered with plastic film

I.6.2.Classification by covering

I.6.2.1. Plastic greenhouses

- Made from various types of plastic (PVC, polyethylene).
- Easy to install.
- Limited lifespan.

I.6.2.2. Polycarbonate greenhouses

- Light weight.
- Provides good thermal insulation.
- Lower cost.

I.6.2.3. Glass greenhouses

- Higher light transmission.
- Provides good thermal insulation.
- More expensive [11].

I.7. Selecting a greenhouse

Selecting a greenhouse requires considering a set of key factors, including [11] :

- The architectural design**.**
- The type of crops to be grown**.**
- Its location and orientation based on climatic conditions**.**
- The farmer's budget**.**

I.8. Climatic factors affecting greenhouses

I.8.1. Solar radiation

Solar radiation is a crucial factor in enhancing crop productivity and quality. It primarily influences the climatic changes occurring inside the greenhouse [12].

Since greenhouses are exposed to sunlight, it is essential to understand the length of daylight throughout the year to select the appropriate crop for cultivation and to take necessary measures in the event of climatic fluctuations [11].

I.8.2. Temperature (T)

A greenhouses are an effective means to enhance plant cultivation by creating a suitable climate for their growth. The main factor influencing the greenhouse environment is solar radiation, which is absorbed by the walls of the greenhouse, causing an increase in internal temperatures in an irregular manner.

In summer:

Solar radiation is strong, causing a significant rise in temperature inside the greenhouse, which can damage crops. To address this issue, mechanical fans or ventilation openings can be used to extract the trapped air and replace it with fresh outdoor air, utilizing wind currents for air renewal. Different types of ventilation can be used depending on the farmer's needs. Additionally, shading screens or cooling systems can be employed to reduce sunlight exposure.

In winter:

Solar radiation is low, making the internal environment of the greenhouse cooler and less suitable for plant growth. It is necessary to heat the greenhouse using gas or fuel boilers, heating devices, or phase change materials to maintain an optimal temperature for the plants [13].

I.8.3. Relative humidity(RH)

Humidity is an important and effective element in regulating the internal climate of a plastic greenhouse. It has a significant impact on plant growth, as plants have the ability to release water through a process known as transpiration, which leads to an increase in internal humidity levels, negatively affecting their growth. To manage this humidity, ventilation is preferred, as it helps expel the humid air and replace it with dry outdoor air. Additionally, systems for removing or absorbing moisture can be used. However, controlling humidity remains a complex task that requires advanced and innovative techniques to adjust effectively [13].

I.8.4. Carbon dioxide (CO_2)

Photosynthesis requires carbon dioxide, but the optimal amount varies depending on the type of plant and its growth conditions. Carbon dioxide constitutes approximately 0.003% of the air, which is the natural concentration required. In greenhouses, however, CO_2 levels can rise to about 0.1% due to the respiration of plants. During the morning, carbon dioxide is consumed from the internal environment until it reaches its optimal concentration or falls below it [11].

I.8.5. Greenhouse Orientation

Adjusting the greenhouse's orientation based on the sun's path and the direction of prevailing winds has presented issues in preventing the heterogeneity of certain climatic conditions within the greenhouse.

In the Mediterranean region, where the sun rises on the horizon, studies have shown that a North-South (N-S) orientation can provide adequate solar lighting. A comparison of morning and evening conditions revealed that this orientation promotes more uniformity of light distribution.

Rosa et al. (1989) advocated a N-S orientation to ensure an equitable distribution of productive solar radiation throughout the year. In terms of light uniformity: The FAO (2013) also advised a N-S orientation, citing the fact that gutter and ridge shadows vary places during the day as the sun moves across the sky. The organization discovered that in some

Mediterranean areas, greenhouses are orientated East-West (E-W), whereas crop rows are aligned North-South to improve crop uniformity [10].

I.9. Controlling the internal climate of the greenhouse

Given the presence of external factors influencing the internal climate of the greenhouse, it is essential to control these factors to create an ideal environment for optimal crop growth. Among the control systems used are Manual Control Automatic or Smart Control Utilizing sensors to measure temperature, humidity, carbon dioxide levels, air volume, as well as cooling, ventilation, and heating systems[11].

I.9. 1 Low-temperature management: heating

Convection, radiation, and transpiration are all elements that influence plant temperature in greenhouses. In the winter, temperatures might fall below the optimal threshold for development, necessitating heating, despite its expensive expense. Heating technologies include [2] :

- Air heating.
- Geothermal energy.
- Solar energy.

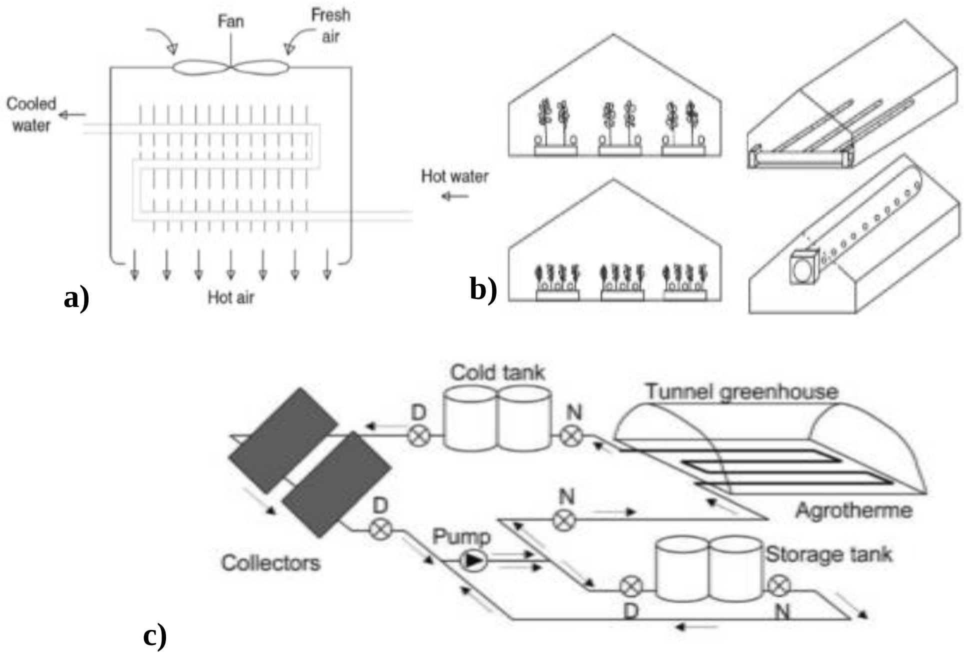


Figure I.5 Heating technologies a) Air heating b)Geothermal energy c) Solar energy[2]

I.9.2 High-temperature management: cooling

Even with sufficient ventilation, plant temperatures in greenhouses can be 5-10°C higher than those in the open air, particularly in hot, arid climates. Ventilation alone is insufficient, and increased humidity is required for optimal crop growth [2] [14].

The following systems can be used :

- Fan-Pad System (**Figure I .6**) .
- Fog/Mist System .
- Shading.
- Natural Ventilation Cooling.
- Forced Ventilation Cooling.

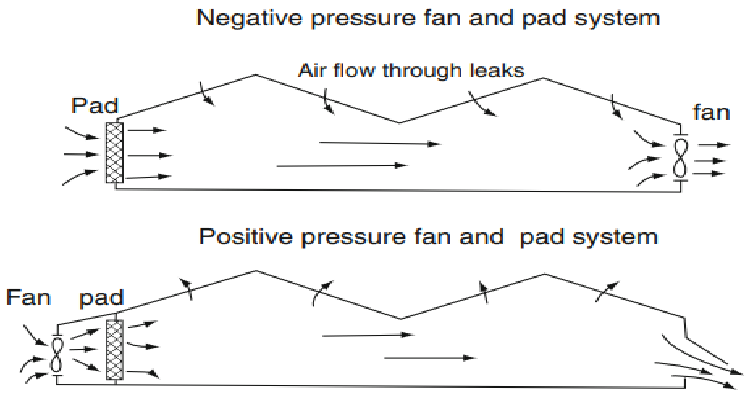


Figure I.6 Negative and positive fan and pad systems[14]

I.10. Ventilation system

To maintain a suitable environment for cultivation inside the greenhouse, ventilation systems are used to balance humidity levels in the air and regulate temperature. There are two main types of ventilation [11]:

I.10.1. Natural ventilation

Natural ventilation is the process of renewing the air inside the greenhouse by exchanging it with outside air. This process aims to remove excess heat and reduce the internal temperature, in addition to regulating humidity levels by expelling air saturated with water vapor resulting from plant transpiration [10]. Achieved primarily through openings or roof vents. It is one of the simplest and most cost-effective methods.

Figure I.7 Natural ventilation[14]

I.10.2. Forced ventilation

Forced ventilation using fans is employed in environments with high humidity levels. It involves fans that draw air out from one side while openings on the opposite side allow fresh air to enter. Although this method is more expensive than natural ventilation due to its reliance on electricity, it offers greater efficiency in controlling air exchange. It will be used in fan and pad cooling systems [14].

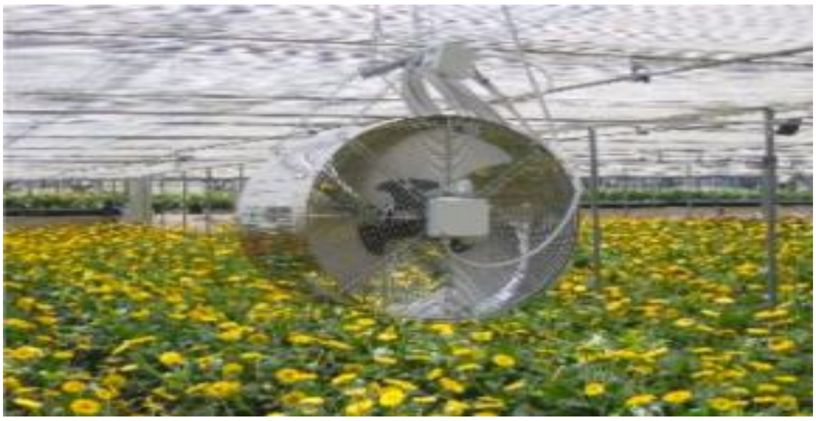


Figure I.8 Forced ventilation [2]

I.11. Solar Heating

Solar energy is used to cover part of the heating demand during daylight hours. To utilize this energy for heating at night, two main challenges must be addressed (according to von Zabeltitz, 1987 and 1988):

1. Converting global solar radiation into thermal energy.
2. Storing this thermal energy for nighttime use.

The conversion of solar radiation into heat is based on three main concepts :

1. The use of separate solar collectors (such as air or water collectors) placed outside the greenhouse, which serve to heat thermal storage units.
2. Integration of solar collectors into the greenhouse structure, where they heat storage media (whether liquid, solid, or air-based).
3. Utilizing the greenhouse itself as a solar collector, where a portion of the incoming solar radiation is absorbed and converted into internal thermal energy.

Thermal energy is typically stored for short-term use (from day to night).

Long-term storage (from summer to winter)requires large storage volumes. Storage materials include gravel, water, solar ponds, soil, and phase change materials (PCM), which are considered one of the most effective solutions for thermal energy storage due to their ability to absorb and release large amounts of heat during phase transitions (from solid to liquid and vice versa) [14].

I.12. Sensible and latent heat storage

I.12.1. Sensible heat storage(SHS)

It is a storage process that can be observed through the change in temperature, as it depends on the heat capacity during the charging and discharging process. It can be expressed by this equation [15][16].

$$\mathbf{Q} = \int_{T_i}^{T_f} m * C_p * dT \qquad \textbf{(I.1)}$$

$$\mathbf{Q} = \mathbf{m} * C_p * (T_f - T_i)$$

Where:

Q [J] : the amount of thermal energy stored (or released).

T_i [K] : the initial temperature of the medium.

T_f[K] : the final temperature of the medium.

m [kg]: the mass of the material used to store thermal energy.

C_p [J/(kg·K)] : the specific heat capacity of the material used to store thermal energy.

I.12.2. Latent heat storage(LHS)

It is a storage process that cannot be observed, and the energy that is absorbed or released is stored during the phase transition at a constant temperature. The materials used for latent heat storage are called Phase Change Materials (PCMs). It can be described by the following equation [15][16].

$$Q = \int_{T_i}^{T_m} m * C_{p\,s} * dT + m * \beta * \Delta h_m + \int_{T_m}^{T_f} m * C_{p\,l} * dT \quad \text{(I.2)}$$

$$Q = m * C_{p\,s} * (T_m - T_i) + m * \beta * \Delta h_m + m * C_{p\,l} * (T_f - T_m)$$

Where:

T_m [K] : the melting temperature,

$C_{p\,s}$ [J/kg·K]: the specific heat capacity of solid PCM.

$C_{p\,l}$[J/(kg·K)] : the specific heat capacity of liquid PCM.

β : the dimensionless fraction of PCM melted.

Δh_m[J/kg] : the heat of fusion per unit mass.

I.13.Overview of PCMs

Natural materials have a high latent heat capacity, which allows them to undergo phase shifts and store heat. This is due to the significant amount of thermal energy required to counteract molecules when transforming from solid to liquid or back to solid. Melting is endothermic, while solidification is exothermic Figure I.8.

PCMs may melt and consolidate at extreme temperatures (0-100 °C) with minimal energy consumption, making them ideal for capturing thermal energy. Power loads can be both transitory and continuous. Heat is released to maintain a consistent temperature and secure electrical circuits. Organic PCMs offer desirable properties such as chemical stability, latent heat capacity, non-corrosion, thermal energy diffusion, and low cost. PCMs are used in several applications, including heating and air conditioning systems, lithium battery packs, solar thermal power systems, and chip cooling [17].

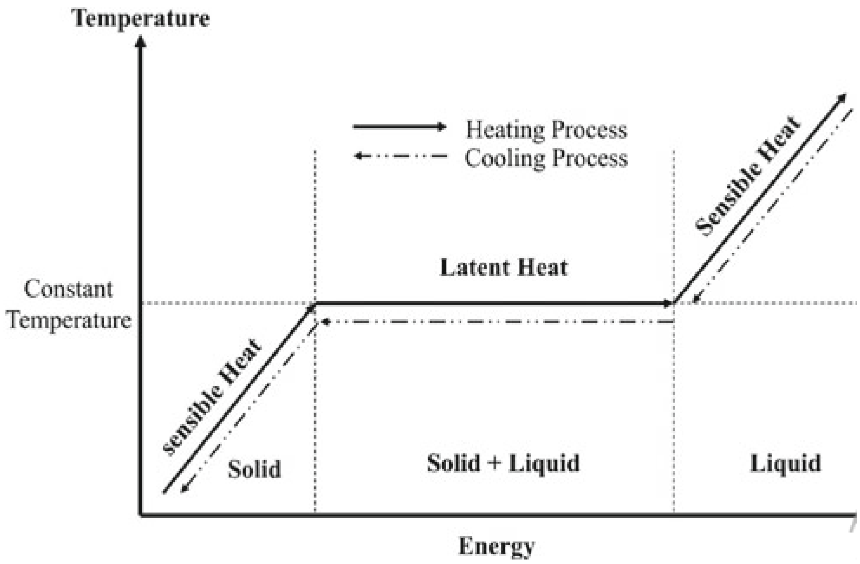


Figure I.9 Temperature changes in PCM during melting and freezing phases [17]

I.13.1. PCM Characteristics

Researchers and scientists are drawn to phase change materials (PCMs) due to their high heat retention and capacity to absorb additional energy. PCMs can accumulate and release energy during their phase transition. process at a constant rate. Materials that do not go through the transition phase cannot store large amounts of energy. Thermal latent energy systems provide a 5-14 times higher energy storage density than sensible heat storage technologies. This is related to the core characteristics of PCMs [17].

Table I.1 of PCM characteristics [17]

Property	Description
High Heat Capacity	Phase change materials (PCMs) have a high heat capacity, allowing them to store large amounts of energy without significant temperature fluctuations.
Latent Heat	PCMs transfer thermal energy without temperature fluctuations during phase transitions (melting and solidification).
Selectable Melting Points	Each PCM has a unique freezing and melting point. These aspects are crucial when selecting a PCM for a specific device.
High Thermal Conductivity	High thermal conductivity allows for efficient and rapid heat transfer between the PCM and its surroundings.
Non-toxicity	PCMs are a safe and environmentally friendly option for thermal energy storage.
Compatibility	PCMs must be compatible with storage device materials and other chemicals they may encounter during their lifespan.
Cost	For commercial applications, PCM prices are critical. High costs of some PCMs may limit their widespread use.

I.13.2.Classification of PCM

PCMs are divided into three groups: organic, inorganic, and eutectics. Organic PCMs can be divided into paraffin and non-paraffin subtypes. The many types of PCMs are summarized in (Figure I.9) [17].

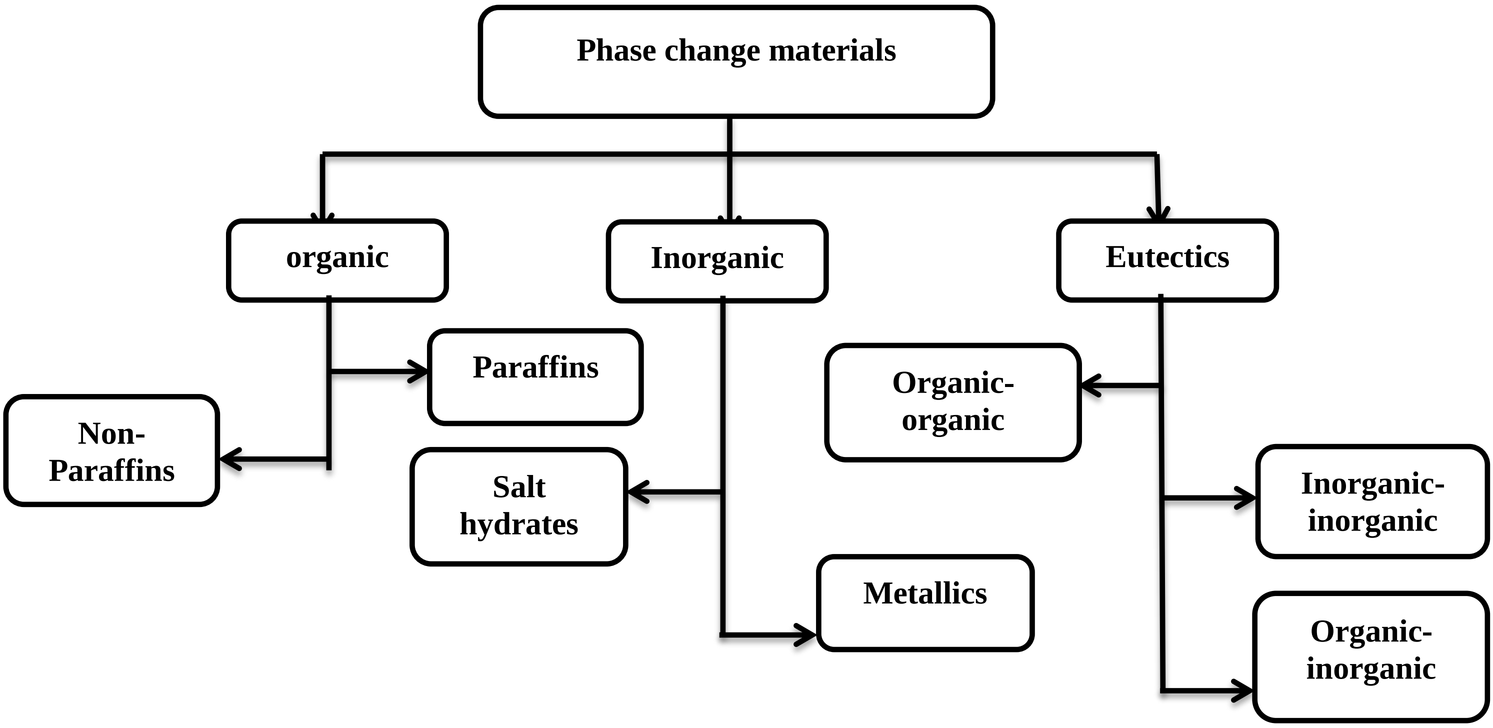


Figure I.10 Classification of PCMs [17]

Table I.2 Potential materials for use as phase change materials (PCM) [18]

	paraffins	Number of carbon atoms in molecule	Melting temp. (°C)	Heat of fusion (J/g)		Density (g/cm^3)
Organic	n-Tetradecane	14	5.8–6.0	227–229		/
	n-Pentadecane	15	9.9–10.0	206		/
	n-Hexadecane	16	18.0–20.0	216–236		0.773
	Salt hydrates	Melting Temp. (°C)	Heat of fusion (J/g)	Thermal conductivity (W/m K)		Density (solid) (10^3 kg/m^3)
				Liquid	solid	
Inorganic	$CaCl_2$-$6H_2O$	28.0–30.0	190–200	0.540	1.088	1.80
	Na_2HPO_4-$12H_2O$	35–45	279.6	0.476	0.514	1.52
	$Zn(NO_3)_2$-$6H_2O$	36	146.9	0.464	/	/
	Eutectic and non-eutectic mixtures	Melting temp. (°C)	Heat of melting (J/g)	Density (kg/m^3)		
Eutectics	45% $CaCl_2$-$6H_2O$ + 55% $CaBr_2$-$6H_2O$	14.7	140	/		
	50% $CaCl_2$ + 50% $MgCl_2$-$6H_2O$	25	95	/		
	51.8% NaF + 34.0% CaF_2 + 14.2% MgF_2	645	/	2370		

I.14. Conclusion

In this chapter addressed the concept of greenhouses and their historical development over the ages, in addition to their types and the climatic factors affecting them. It also discussed the methods used to control these factors in order to efficiently enhance agricultural production, with a focus on solar-powered heating systems and the use of effective materials in this field.

Chapter II:Literature review

II.1. Introduction

After the world witnessed an increase in population density and challenges in securing food, these challenges were further exacerbated by climate change and its impact on agricultural crops and their quality. The idea of plastic greenhouses emerged as an ideal solution for crops, as they provide suitable conditions such as light, heat, humidity, and carbon dioxide. However, challenges related to heating and cooling costs still persist, leading to the adoption of renewable energy sources [8].

This chapter will review previous studies conducted by researchers on the use of heating systems in plastic greenhouses through solar energy and the materials used for this purpose [12].

Berroug et al. (2011) examined the thermal performance of a north-facing wall in an agricultural greenhouse. They used a phase change material ($CaCl_2 \cdot 6H_2O$) as a heat storage medium. A numerical model was created that included the greenhouse's essential components. Climatic data from January in Marrakesh were used. Using 32.4 kg of PCM per square meter increased overnight air and plant temperatures by 6-12 °C and reduced relative humidity by 10-15%, resulting from improved convective and radiative heat transfer within the greenhouse [19].

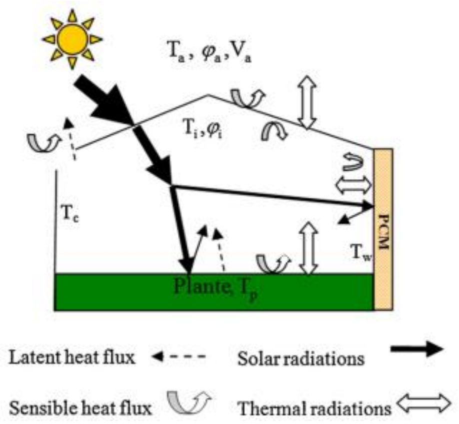


Figure II.2 Energy balance of .greenhouse components[19]

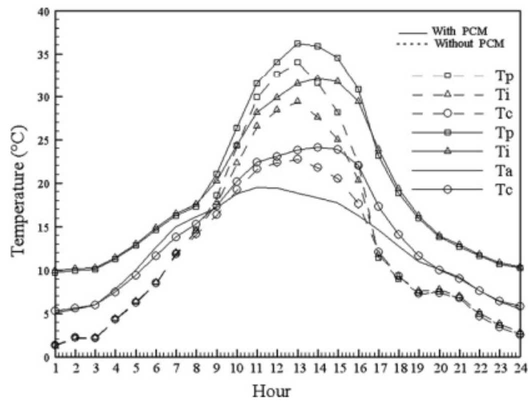


Figure II.1 Hourly variation of the outside air temperature, plants, cover and inside air temperature with and without PCM NW for a typical climate day of January in Marrakesh [19]

In order to assess the effectiveness of a ground-source heat pump-based heating system with a latent heat storage tank, **Benli (2011)** used phase change material (PCM) in tiny glass greenhouses with a heating area of 30 m². A horizontal ground heat exchanger measuring 246 meters in length and 12.7 mm in diameter was employed in the system. According to the findings, the coefficient of performance (COP) varied between 2.0 and 3.8. According to the study, using PCM improved thermal stability within the greenhouse and decreased energy use [20].

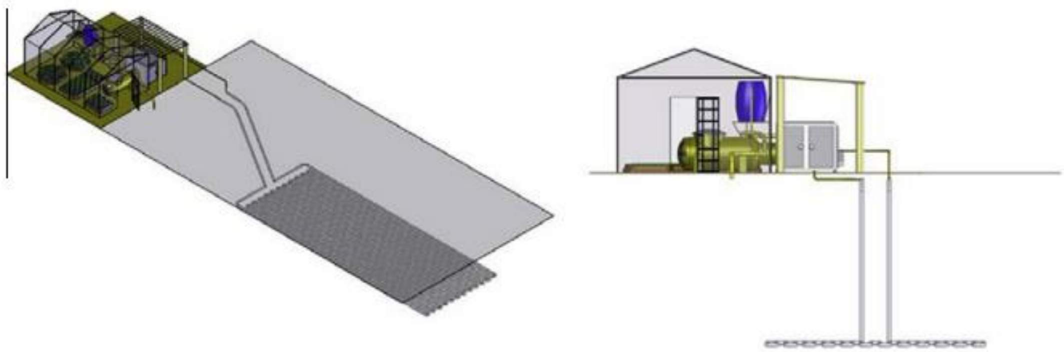


Figure II.3 Experimental equipment of the greenhouse heating system [20]

Beyhan et al. (2013) conducted a study to test a new technique for regulating root-zone temperature in soilless greenhouses using phase change materials (PCM). Various blends of fatty acids, along with two types of paraffin (Rubitherm-RT2, Rubitherm-RT35), were tested on zucchini and pepper plants without any additional heating systems. The results showed that a mixture of 40% oleic acid and 60% capric acid increased root-zone temperature by 1.9°C for zucchini and 2.4°C for pepper, proving to be more efficient than pure oleic acid [21].

Table II.1 Growth parameters of the plants used in the tests [21]

Vegetable	Seed germination temperature (°C)	Optimum soil temperature (°C)	Optimum growth temperature (°C)	
			Day	Night
Zucchini (cucurbitePepo)	10	15.5	20-25	7-13
Pepper (capsicumAnnum)	8-10	17	18-25	14-16

Table II.2 Properties of materials selected to prepare PCMs as given by manufacture [21]

	Melting point (°C)	Molar mass(g/mol)	Density (g/cm^3)	Flash point (°C)
Oleic acid	16	282.46	0.89(20°C)	180
Capric acid	29-32	172.26	0.89(20°C)	150
RT2	2-5	/	0.77(15°C)	102
RT35	35	/	0.88	178

(Guan et al., 2013, 2012) examined the passive heat storage capability of APTPCMW. The passive heat storage capacity was 1.18 times higher than the north wall without PCM wallboards, with 77.6% stored in the PCM wallboards. This study presents results from an experiment evaluating the active performance of APTPCMW, identifying influencing elements, and determining optimal operating parameters [22].

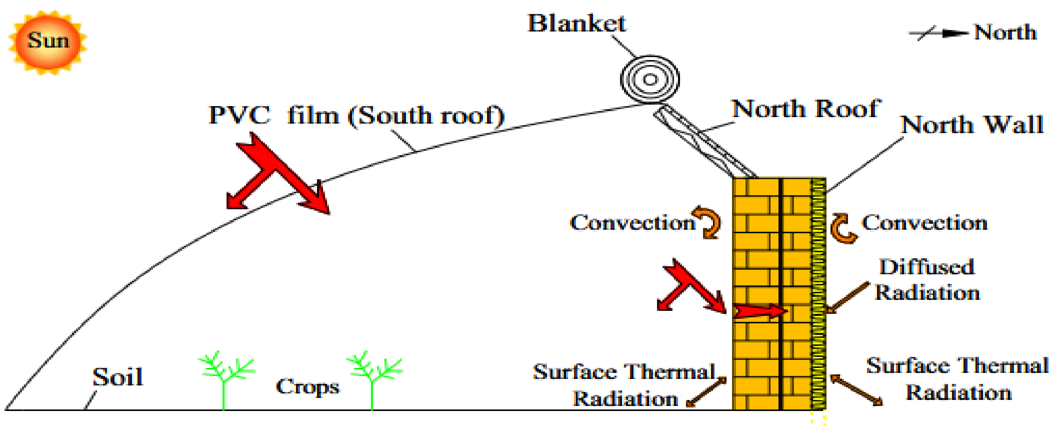


Figure II.4 A schematic diagram of the solar greenhouse [23]

Li et al. (2014) explored the application of phase change material (PCM) in Chinese-style solar greenhouses, with spinach (F1 variety) as a test plant. The findings indicated that PCM, namely butyl stearate with a phase change temperature of roughly 18°C, substantially reduced temperature swings within the greenhouse. Compared to a typical greenhouse, PCM helped reduce daytime peak temperatures by 1-2°C, boost nighttime minimum temperatures by 1-3°C, and reduce overall indoor temperature variance by 1-2°C [24].

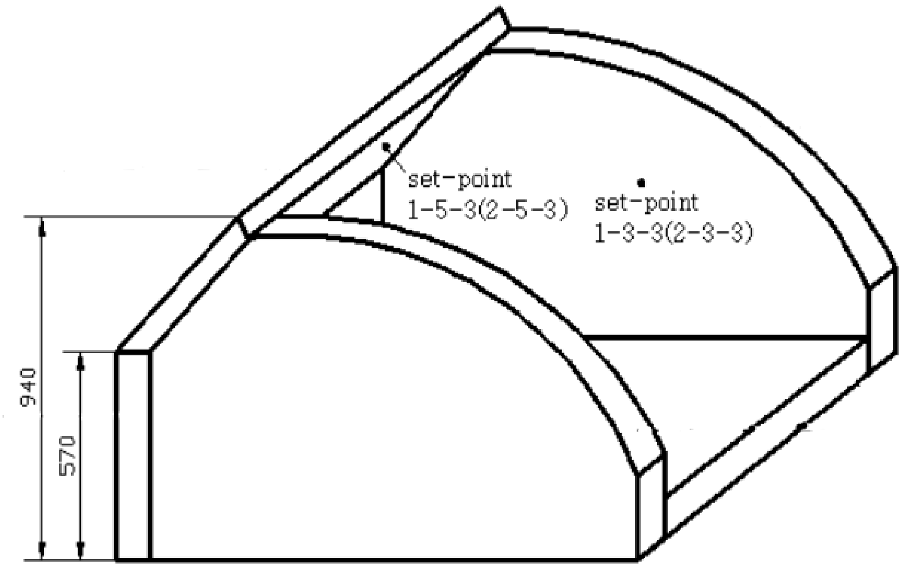


Figure II.5 greenhouse model [24]

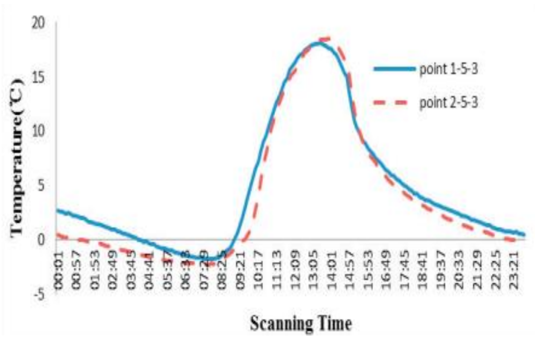


Figure II.7 Comparison of point 1-5-3 and point 2-5-3 [24]

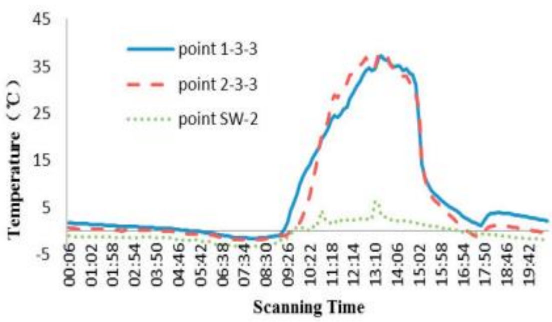


Figure II.6 Comparison of point SW-2 point 1-3-3 and point 2-3-3 [24]

Chen et al. (2018) developed an active-passive ventilation wall using Phase Change Material (PCM) to increase greenhouse thermal performance. The study compared the suggested wall to a standard one, and found that the new wall raised the temperature of its middle layer and exposed surface. The wall's heat storage capacity grew by 35.27–47.89%, while its heat release capacity increased by 49.93–60.21%. This caused a rise in indoor air temperature, soil temperature, and daily cumulative effective temperature. Plant growth was enhanced, with a 30% rise in plant height, 25% in stem diameter, and 28% in fruit yield. The suggested wall resulted in higher daily and total fruit yields in the greenhouse than the traditional wall [25].

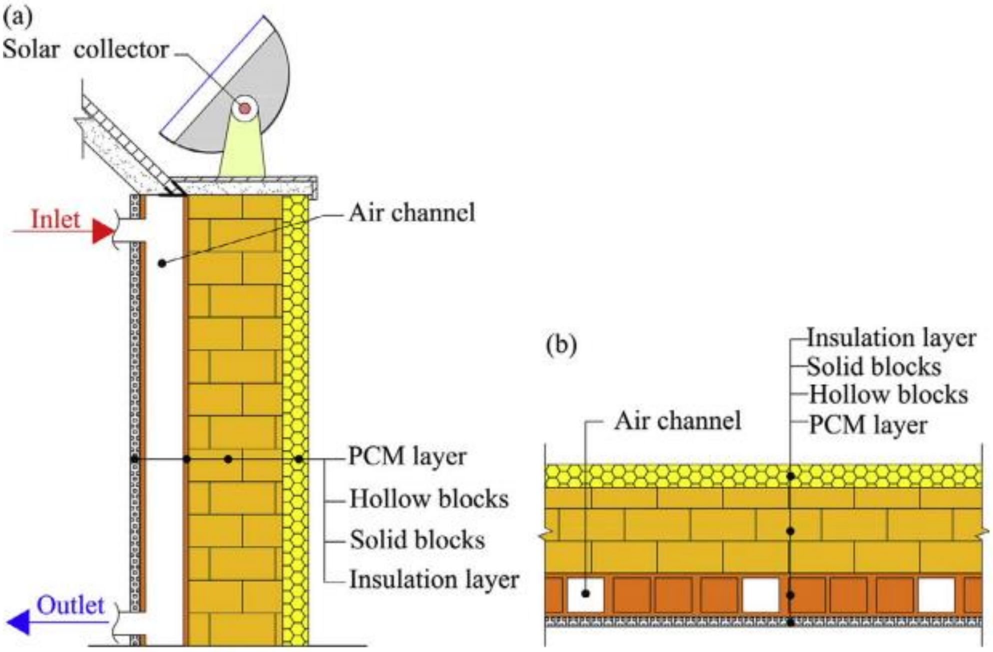


Figure II.8 Schematic diagram of the active-passive ventilation wall with PCM: (a) vertical section; (b) horizontal section [25]

In 2019, Baddadi et al. built a hydroponic greenhouse in Tunisia using a solar air heater with latent thermal storage and Phase Change Materials (PCM) for heating. The results indicated that this design provided a better environment than typical greenhouses. During the day, the temperature within the greenhouse can rise over 18°C, with a temperature difference of up to 6°C between the inside and outside. The greenhouse's temperature increased to 15°C in the evening and remained over 32°C all day. In comparison to standard solar heating systems, latent thermal storage considerably improved the indoor atmosphere during extreme weather conditions and at night [26].

Figure II.9 The experimental Heated Hydroponic Greenhouse [26]

In 2019, Naghibi et al. used the TRNSYS program to evaluate the advantages of incorporating Phase Change Material (PCM) into a solar heating system's water tank. They used TRNSYS to calculate the hourly heating demand of a reference greenhouse, and used a validated model to investigate the impact of PCM on system efficiency. Four distinct configurations were tried, with PCM volumes of 20%, 40%, and 60%.The findings revealed that raising the PCM fraction might boost the system's energy efficiency by 10% to 14% [27].

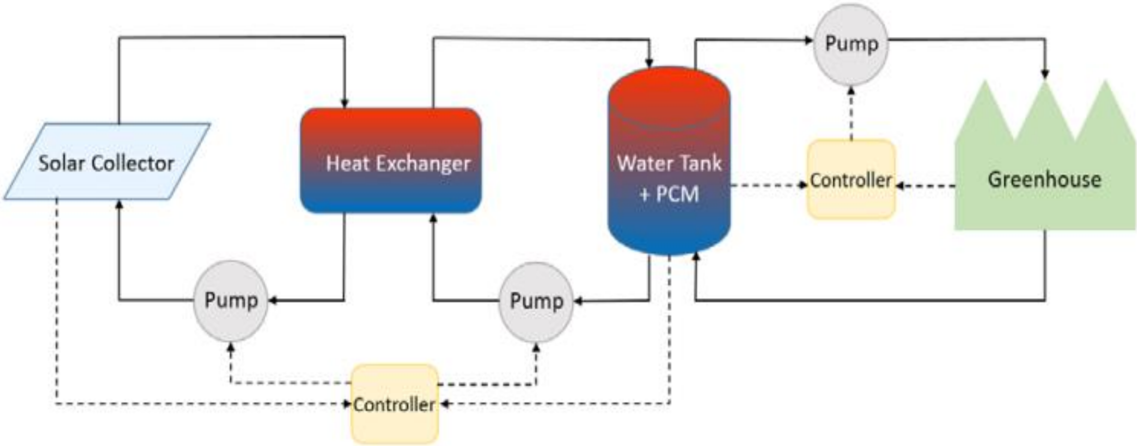


Figure II.10 TRNSYS Model Component diagram [27]

In 2020, Yan et al. built agricultural greenhouses and investigated the impacts of two waste heat recovery (HRS) systems, one with and one without Phase Change Material (PCM), on heating systems. The findings revealed that the PCM-integrated HRS improved energy efficiency by 40% and exergy efficiency by 263%. It also saved 19% on fuel, compared to the 48% saved by the system without PCM. The payback period for the PCM-integrated HRS was three months, whereas the non-PCM HRS was four months [28].

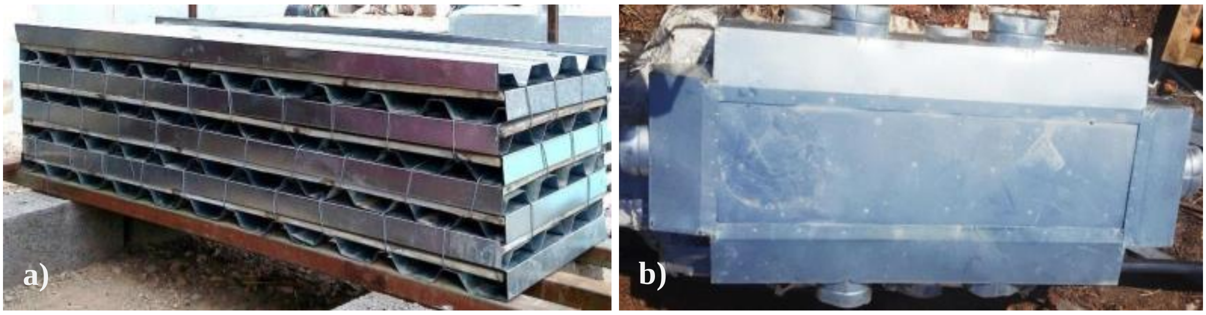


Figure II.11 A photographic view of PCM HRS a) the interior b) the exterior [28]

Azaizia et al. developed a new solar greenhouse drying method **in 2020** that used a paraffin-based Phase Change Material (PCM) to improve red pepper drying. The PCM-based system had greater thermal performance, with air temperature remaining 7.5°C higher at night and relative humidity decreasing by 18.6% after sunset. The drying period was dramatically lowered to 30 hours, vs 55 hours without PCM and 75 hours with open sun drying [29].

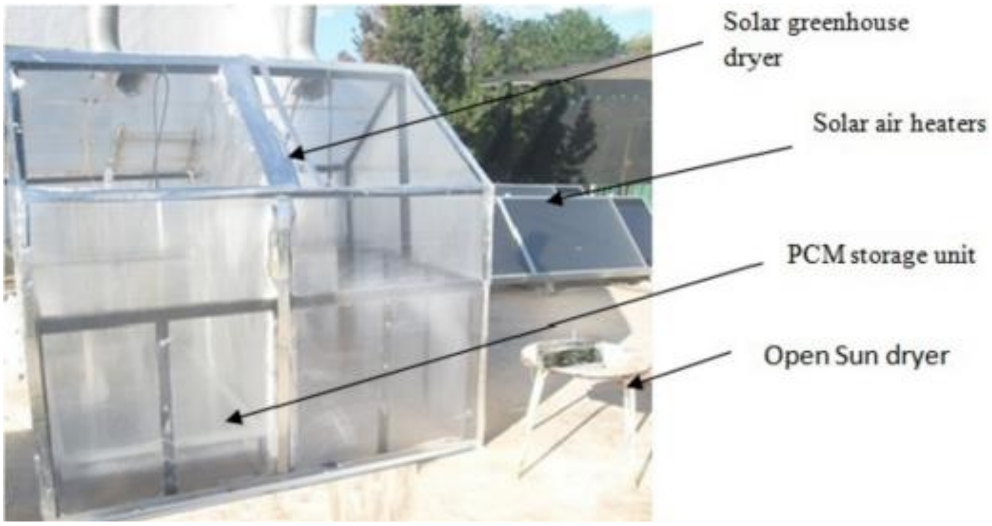


Figure II.12 Experimental solar greenhouse drying system [29]

In 2020,Chen et al. presented a latent heat storage system using Phase Change Materials (PCM) for agricultural plastic greenhouses in both hot and cold climates. Based on a pilot study in southern China, the researchers built a test greenhouse and a computer model to construct efficient, all-day winter operations. The experimental findings validated the proposed strategy's effectiveness as well as the numerical model's accuracy. The proposed system maintained an internal air temperature of at least 10 °C, compared to 3.7 °C without PCM. The numerical model also contributed to the development of more feasible PCM and thermal insulation solutions. The analysis found that the system is economically viable, with a payback period that is shorter than its operational life [30].

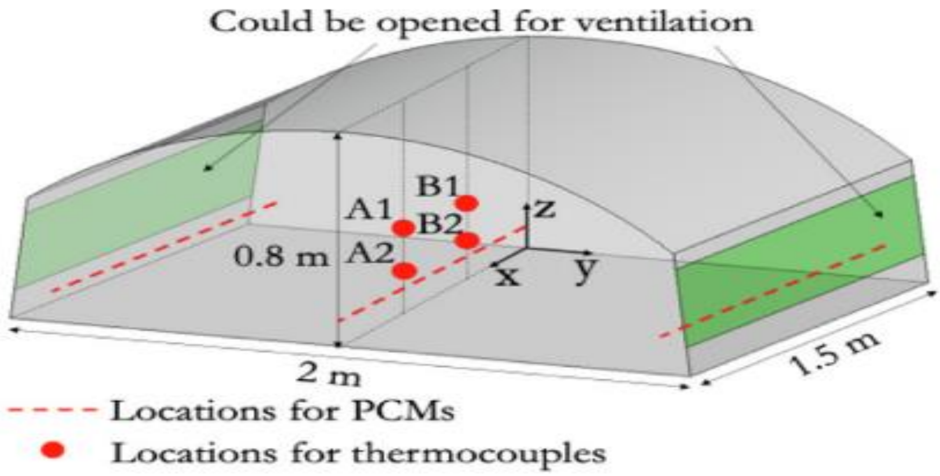


Figure II.13 Experiment setup and digital model [30]

Xiaoyun et al. (2021) used the enthalpy approach to simulate the effect of phase change materials (PCM) on indoor temperatures in solar greenhouses in Xi'an, China. The findings revealed that PCM is more successful than standard heat storage materials at regulating indoor temperature, contributing to higher minimum temperatures and fewer fluctuations. The ideal thermal characteristics of PCM for the location were determined as a phase change temperature of 11°C, latent heat of 140 kJ/kg, and thermal conductivity of more than 0.4 W/(m·°C) [31].

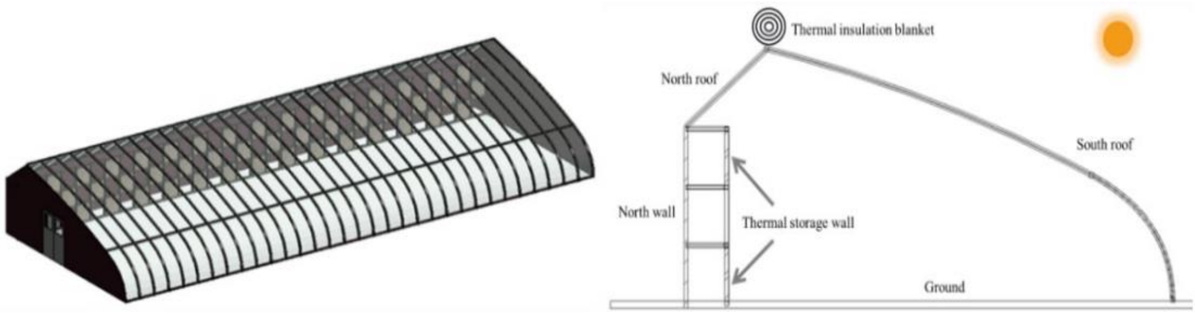


Figure II.14 Solar greenhouse model [31]

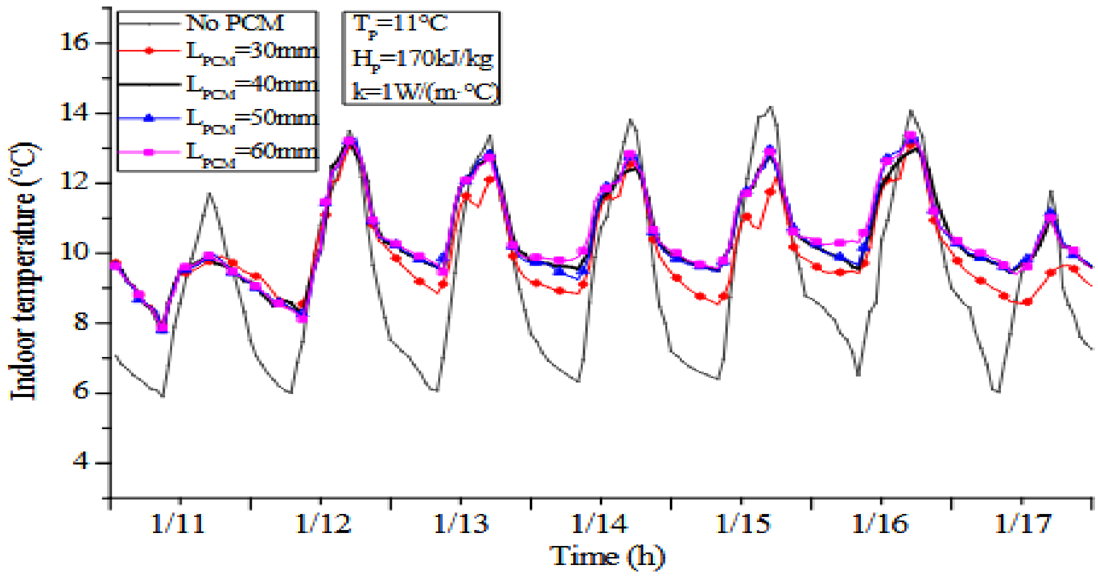


Figure II. 15 Influence of heat storage material on indoor temperature of solar greenhouse [31]

Yan et al. (2021) investigated a solar greenhouse in a plateau area in central Yunnan, using phase change materials (PCM) to measure their effect on indoor temperatures under varied climatic circumstances. The findings revealed that PCM greatly improved thermal conditions within the greenhouse, particularly in the face of major day-night temperature differences. The most influential components were discovered to be solar radiation, the external day-night temperature differential, and the average outdoor air temperature. PCM also helped to reduce internal temperature swings, which became more obvious as the ambient temperature climbed, resulting in a considerable reduction in daytime temperature disparities inside the greenhouse compared to outside [32].

Figure II.16 Greenhouse structure [32]

Li et al. (2022) studied a plastic greenhouse in Chengdu to investigate the thermal environment throughout the winter and evaluate a previously constructed energy balance model. The findings revealed that the soil acted as a thermal mass at night, contributing to an increase in temperature near the ground, with a temperature difference of 4 to 6°C found between the interior air and the soil. The study recommended using phase change materials (PCM) to improve the effectiveness of ground thermal storage. The addition of PCM increased the soil surface temperature by 1°C and improved the ground thermal storage conversion efficiency by 7% when compared to greenhouses without PCM [33].

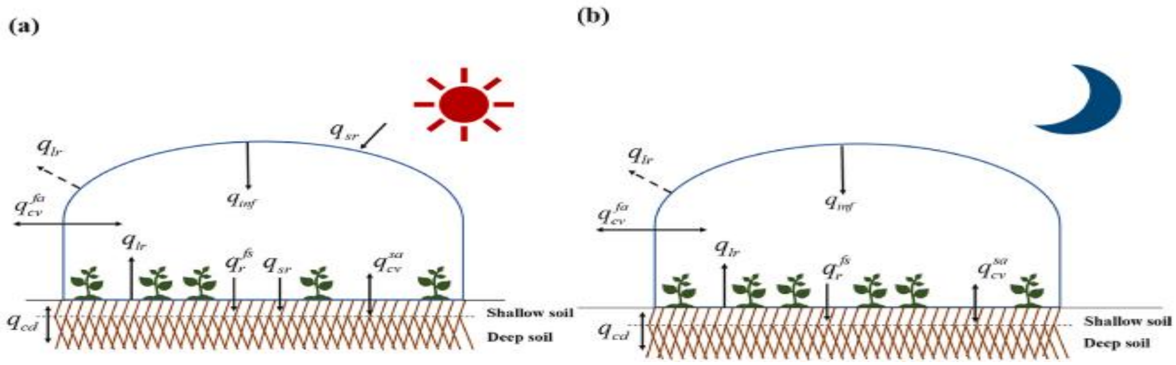


Figure II.17 Energy transfer models in solar plastic greenhouses

((a) daytime, (b) night time) [33]

Jahangir et al. (2022) investigated the application of organic fatty acid ester-based phase change materials (PCMs) in greenhouses to improve energy efficiency. Using the DesignBuilder and EnergyPlus simulation tools, the results revealed that yearly electricity savings of up to 14,577 kWh were possible, particularly with the usage of bioPCM-Q27. Furthermore, phase change materials contributed to a reduction of natural gas usage during cold seasons, with possible annual savings of up to 1,348 kWh [34].

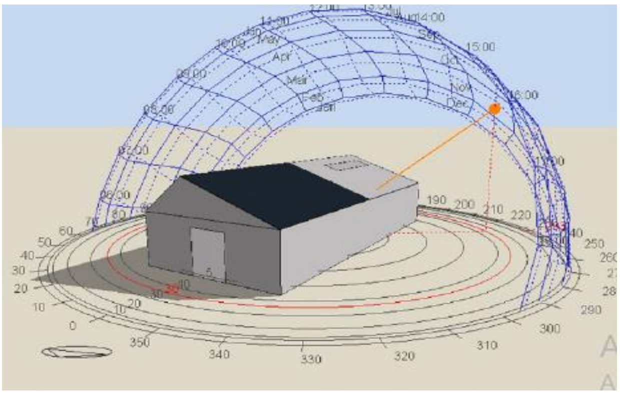


Figure II.18 The 3D model of the designed greenhouse (Designbuilder software) [34]

Sehrawat et al. (2023) investigated the financial and environmental consequences of the BIPVTGDPCM system, which is a thermal greenhouse drying system that incorporates phase change materials. The system was tested at Rohtak, Haryana, India. The findings revealed that including PCM (Lauric acid) enabled the system to continue running long after sunset. A total of 49,851 kg of CO2 emissions were discharged, and the system received carbon credits worth $498,514 USD. The financial payback period was 2.6 years, and the energy payback period was 2.14 years. The BIPVTGDPCM system proven to be an environmentally benign food preservation solution with thermal, electrical, environmental, and economic advantages, making it a long-term and future-proof solution [35].

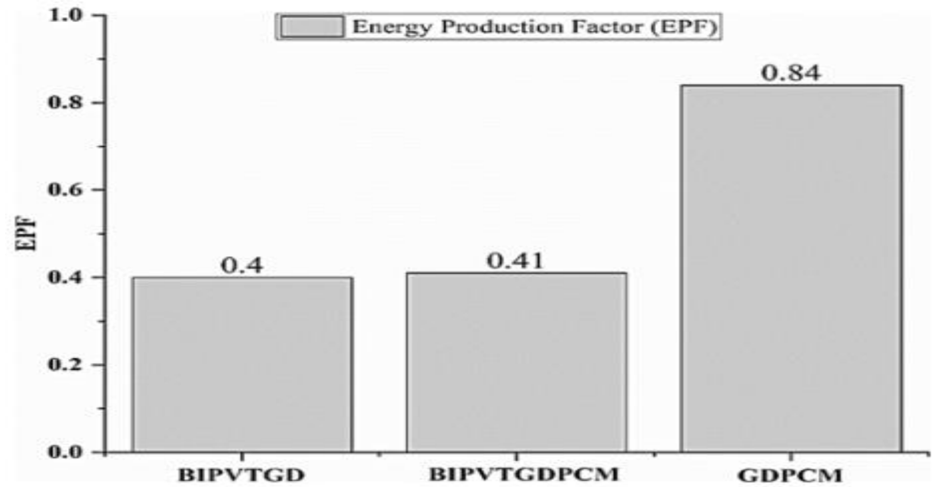


Figure II.19 EPF for different GD combinations [35]

Badji et al. (2023) designed, built, and tested a thermal energy storage unit for greenhouses using phase change materials (PCM). The study sought to assess the effectiveness of these units in improving air temperature in greenhouses. The study found that greenhouses with PCM had a 1 to 8 °C increase after midnight compared to conventional greenhouses. The researchers also presented viable PCM installation options and developed an operational plan to reduce energy usage in solar greenhouses throughout the winter season [36].

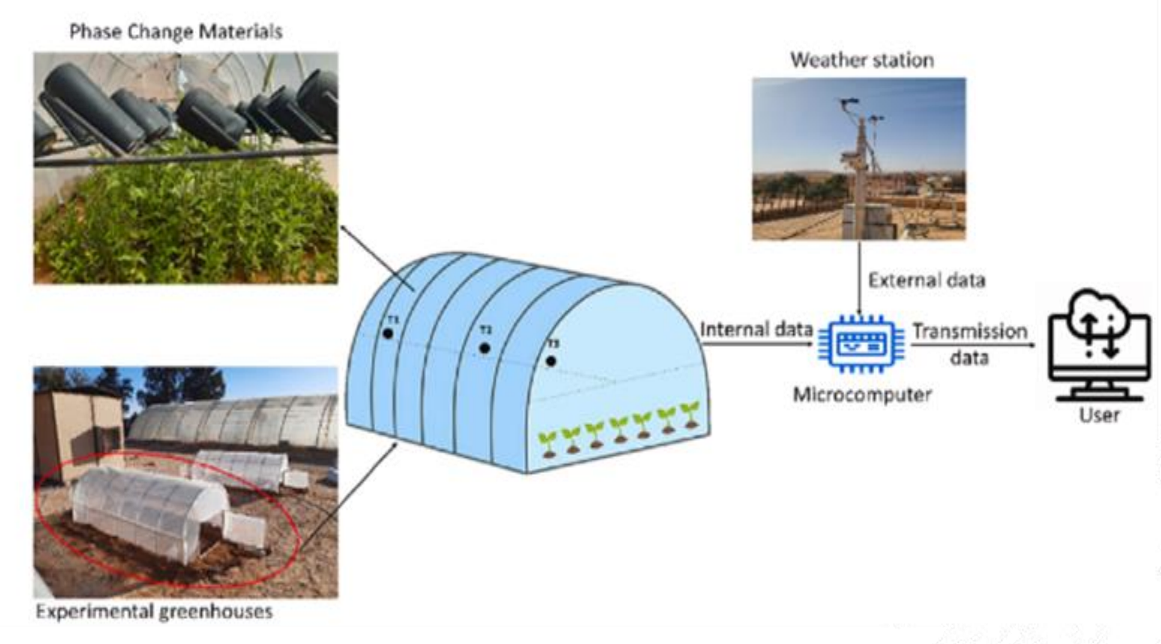


Figure II.20 Experimental setup [36]

Ismail et al. (2023) found that incorporating phase change materials (PCMs) significantly improved the thermal efficiency of passive solar greenhouses in cold climates. The study examined two types of paraffins: n-Tetradecane and n-Pentadecane. Due to its higher melting point and greater heat capacity, n-Tetradecane resulted in a 3 to 10°C increase in the average internal temperature of the greenhouse, making it the more effective option. Installing PCM on the north side of the greenhouse notably enhanced heat retention, providing an efficient method for reducing nighttime heat loss in colder climates. However, the researchers noted that while n-Pentadecane also contributed to improved internal temperatures, it did not fully reach the optimal range for crop growth, highlighting the importance of selecting PCM types that are specifically suited to the climate conditions of the region [37].

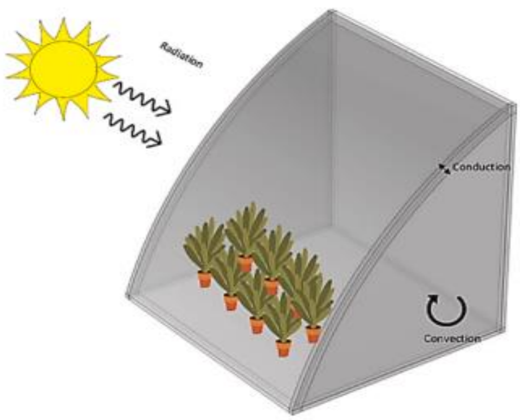


Figure II.21 Heat transport modes applied to The simulation model [37]

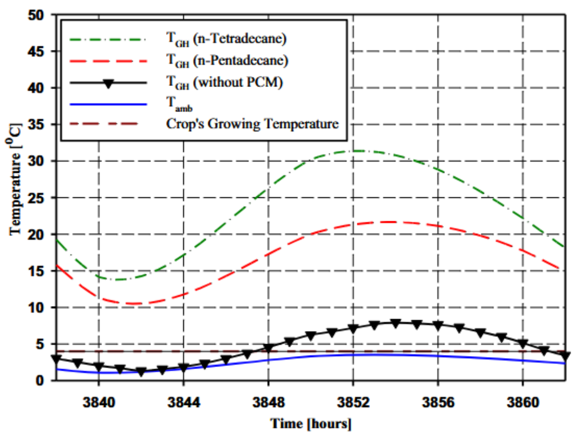


Figure II. 22 Simulation results for the greenhouse model on June, 10th [37]

BADJI, A. (2024). conducted a study on a heating system using solar energy inside a plastic greenhouse in the Ghardaïa region of Algeria (semi-arid climates). The greenhouse was connected to a solar air heater, which was linked to a pipe containing Phase Change Materials (PCMs) that absorb and store heat during the day and release it during the night Figure II.23 Additionally, artificial intelligence techniques were used to predict the internal air temperature of the greenhouse. The results were found to be suitable for climatic conditions similar to those of this region [4]**.**

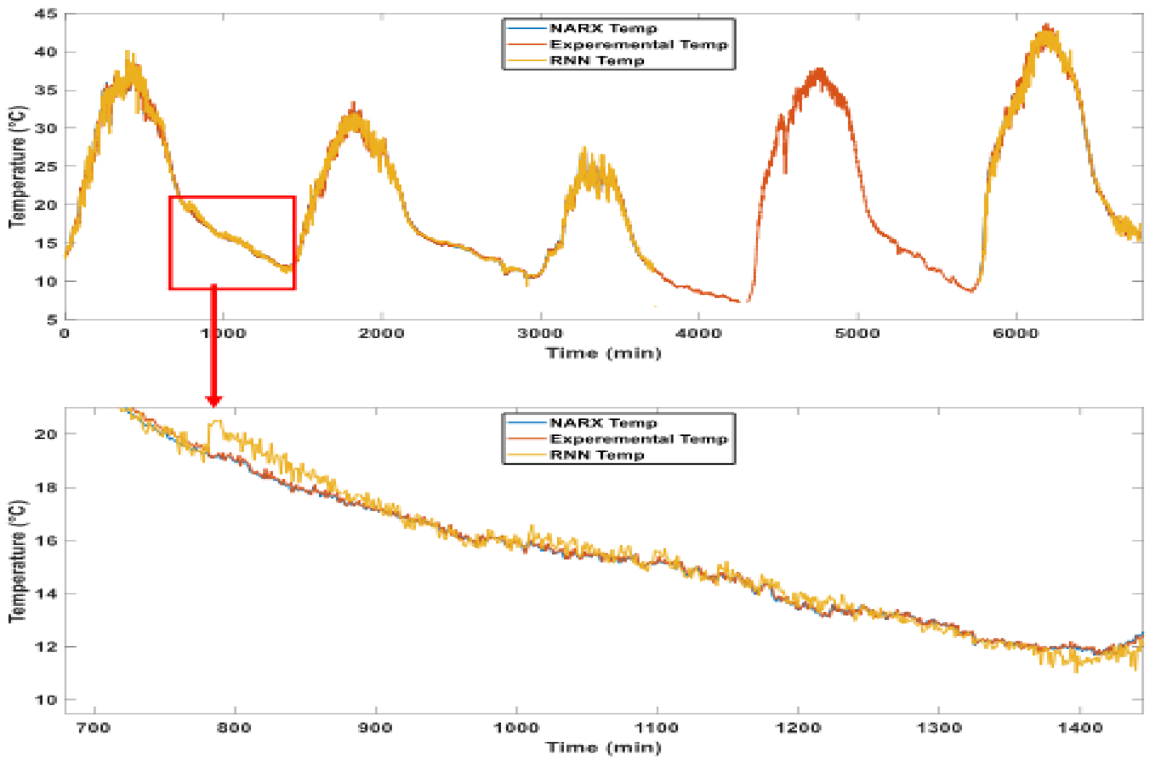


Figure II. 23 Output of ANNs models with LTES [4]

II.2. Conclusion

This chapter reviews previous studies on the use of phase change materials (PCMs) in the agricultural sector, specifically in plastic greenhouses, to improve agricultural production. These experiments proved to be highly effective, especially in heating systems. These materials have the ability to melt and solidify at different temperatures, and in addition, they are environmentally friendly and cost-effective. For this reason, farmers have turned to relying on them to improve the quality of their crops and make them available outside of their seasons.

Chapter III:Material and Methods

III.1. Introduction

The desert occupies a large part of Algeria's territory, with desert regions characterized by a hot and dry climate in summer and a drop in temperatures during winter, which affects the agricultural environment inside greenhouses. Due to these conditions, agriculture faces significant challenges in maintaining an optimal temperature for crops. In this context, a greenhouse heating project was launched in the Ghardaïa region to improve agricultural performance.

To regulate thermal conditions inside the greenhouse, temperature control must be achieved through various systems, including the solar heating system, natural and forced ventilation systems, and more.

In this chapter, we will provide an explanation of the equipment and tools used in the experiment, as well as the devices employed for data collection to ensure accuracy and reliability through a comprehensive study of the experiment [12][8].

III.2. Experimental site

III.2.1. Location and geographical features

We conducted this experiment at the Applied Research Unit for Renewable Energies (URAER), located in the Ghardaïa region at a latitude of 32.43° North and a longitude of 3.45° East [8].

Figure III.1 The location of Ghardaïa

This area is characterized by several climatic and geographical features, including :

Table III.1 Study Site Characteristics in Ghardaïa [8]

Characteristic	Value
Location	595 km south of the Mediterranean Sea
Altitude above sea level	469 meters
Annual sunshine days rate	77%
Average global solar radiation (daily)	7 kW/m²
Highest monthly solar radiation level	6000 W/m² (June - July)
Maximum recorded temperature	42°C (June - July)
Lowest monthly solar radiation level	2900 W/m² (January - December)
Minimum recorded temperature	10°C (January - December)

III.2.2. Overview of the Applied Research Unit in Renewable Energies (URAER)

In 1999, the Applied Research Unit in Renewable Energies(URAER), affiliated with the Center for Renewable Energy Development (CDER), was inaugurated in the municipality of Bounoura, Ghardaïa province. This unit has facilitated researchers in conducting experiments related to renewable energies.

It consists of two distinct divisions :

- The Small Solar Power Plants Division**.**
- The Renewable Energy Applications in Desert Areas Division**.**

Each division has specialized research teams dedicated to developing applications in the field of renewable energies. In addition, a research field has been provided for master's and doctoral students to carry out their final research projects [17].

Figure III.2 a)Applied Research Unit in Renewable Energies (URAER) Ghardaïa.

b) Experimental platform for applications of renewable energies in agriculture

III.3. Experimental greenhouses

The experimental study was conducted within the experimental field for renewable energy applications in agriculture, where the performance of a heating system was tested in two scaled-down models of double-span plastic greenhouses (1/10 of the actual size) with identical dimensions (length: 2 m, width: 1.6 m, height: 0.65 m) and a floor area of 3.2 m² for each greenhouse, oriented in a North-South direction. Each greenhouse was equipped with a door made of polycarbonate to ensure thermal insulation and minimize heat loss as much as possible[12].

Climatic parameters inside and outside the greenhouses were measured over a specific period using an advanced radiometric station to collect solar radiation data every 10 minutes. Additionally, temperature and humidity were measured using SHT31 sensors and K-type thermocouples, with data recorded every minute using an Arduino Mega 2560,data collection and later analyzed on a computer [4] **.**

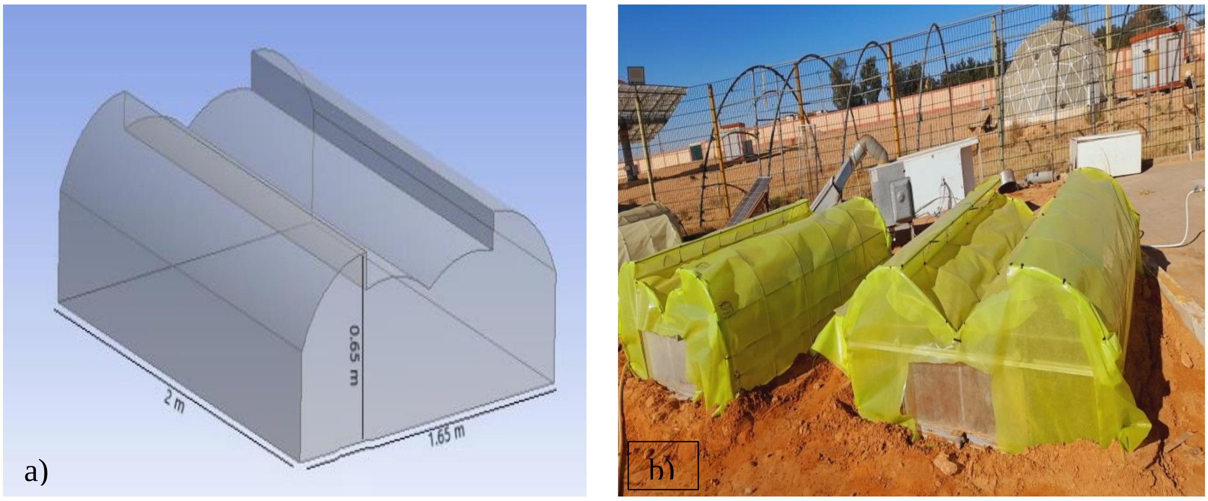
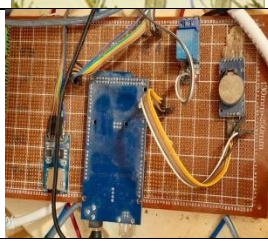


Figure III.3 a) The schematic of greenhouse[4]. b) Experimental greenhouse

Table III.2 Uncertainty instruments

Instrument name (Model name)	Usage	Range /max	accuracy	Resolution/ readability	Material
12 channels temperature recorder (BTM-4208SD)	Data collection	12channels	/	0.1/1	
Pyranometer (EKO MS-64)	Solar irradiance	0 to 2000 $W/_{m^2}$	$\mp 0\cdot 51$ $W/_{m^2}$	/	
Thermocouple type K(Nichel – Chrome/nichel –Aluminum)	Temperature	-200℃to $+1350$℃	$\mp 2\cdot 2$℃	0.1℃	
Humidity and temperature sensor (SHT31)	Humidity	$0\%to\ 100\%$ RH	$\mp 2\%RH$	$0.1\%RH$	
	Temperature	-40 -125℃	$\mp 0\cdot 2$℃	0.1℃	
Arduino mega 2560	Control and data acquisition	/	/	/	

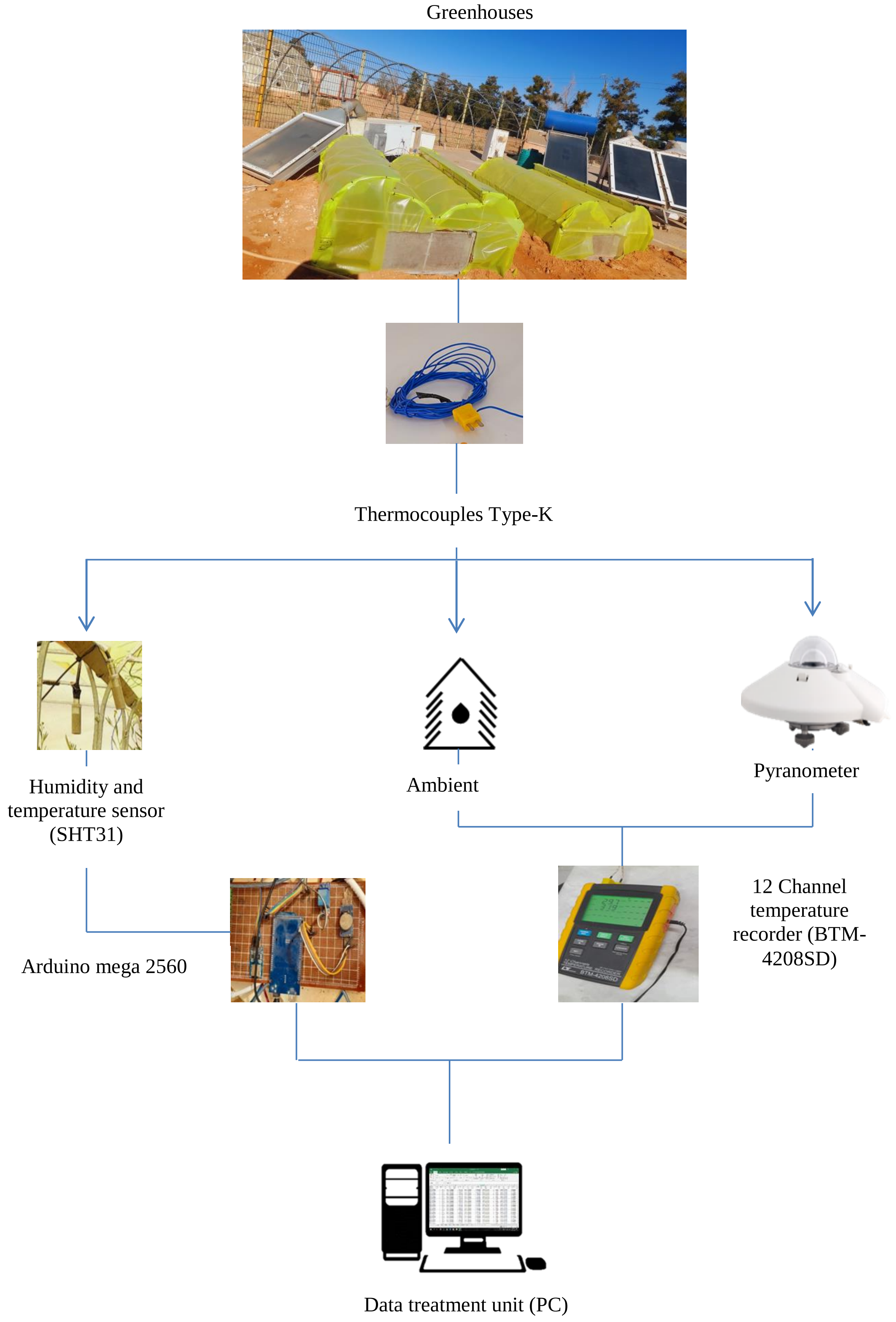


Figure III.4 Data acquisition system

III.4. The selection of calcium chloride in thermal energy storage

We chose calcium chloride hexahydrate (**$CaCl_2,6H_2O$**), which is a type of hydrated salt, as it is one of the most commonly used materials in latent heat storage applications, especially for thermal energy storage in greenhouse heating systems**.** Its suitable thermal properties include high

which plays a key role in improving storage[38]**.**

Additionally, it has a high specific heat capacity (**652 J/kg·K**) at 25°C compared to other storage materials[4], and high thermal conductivity, enabling rapid and efficient heat transfer[39]. (**$CaCl_2,6H_2O$**) also has an appropriate melting temperature of 29°C, making it suitable for thermal comfort applications[38] **.**

Moreover, (**$CaCl_2,6H_2O$**) is inexpensive, non-toxic, and environmentally friendly, making it an economically viable option for storage systems[12].

III.5. The experimental protocol for preparing calcium chloride

Calcium chloride $\mathbf{CaCl_2}$ is a white solid under standard thermal conditions, and it exists in its crystalline form , $\mathbf{CaCl_2{,}6H_2O}$. Its molecular weight is ($\mathbf{M = 219{,}08\,g/mol}$), and it contains salt and water in proportions of 50.66% and 49.34%, respectively. It is soluble in water, and when it reacts with water, it forms hydrates while releasing heat [12].

We weighed 284 g of calcium chloride using a scale, then added 400 g of distilled water. First, we placed the calcium chloride inside a glass beaker, poured the water over it, stirred it with a special spoon, sealed the beaker, and then placed it on a mixer to ensure homogeneity at a temperature of 60°C.

Finally, after preparing the required amount, it was placed into 33cl capacity cans**.**

The following figures illustrate the tools used in the experiment :

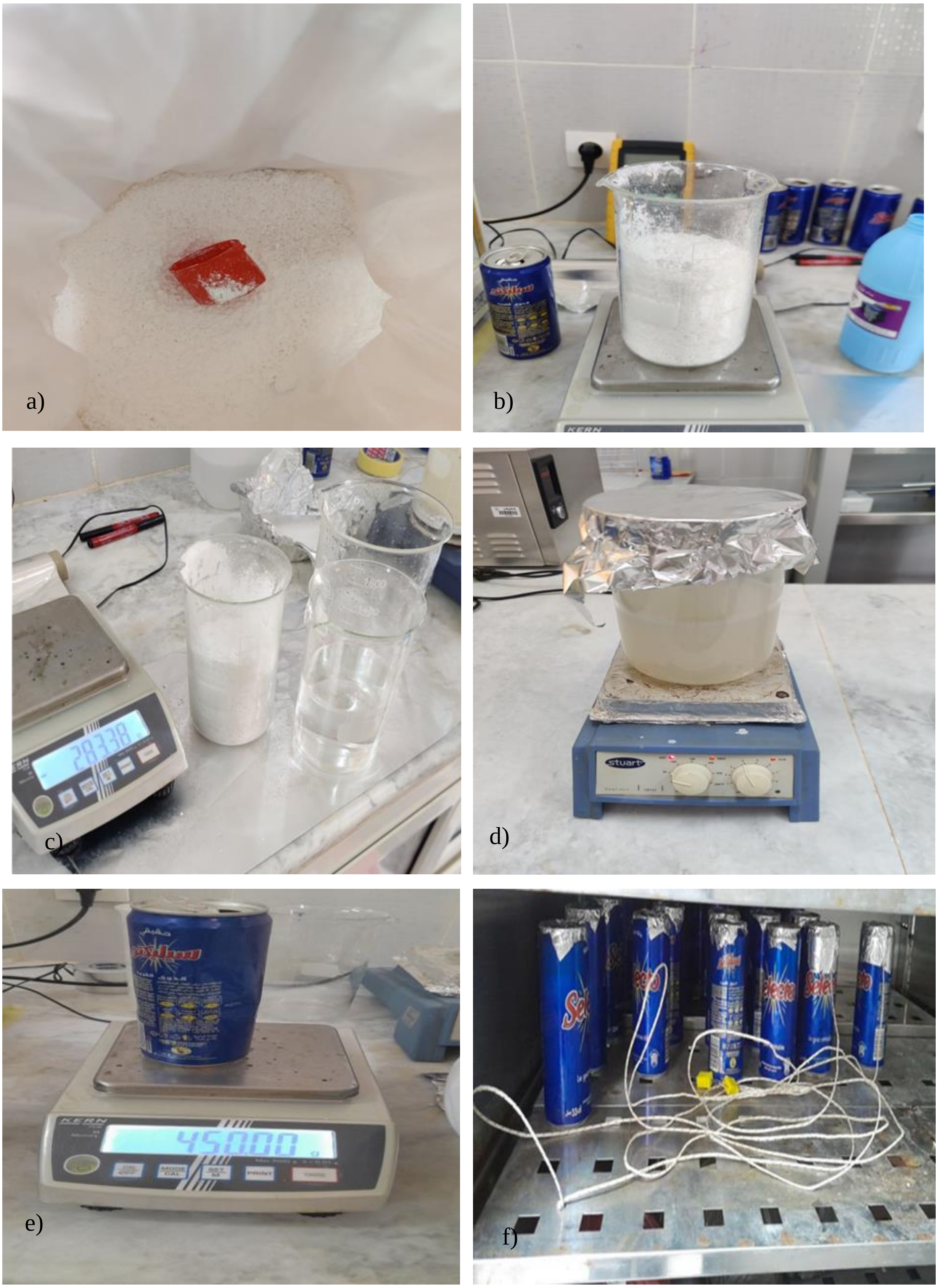


Figure III.5 a) Crystalline $CaCl_2,2H_2O$ b) Quantity of $CaCl_2,6H_2O$ c) Quantity of $CaCl_2,6H_2O$ and distilled water d) Mixing the mixture e) PCM cans mass (g) f) Final state

calcium chloride at a temperature around 29 °C according to the following reaction [8]:

(**Ca** $\boldsymbol{Cl_2}$, $\boldsymbol{2H_2}$**O**) + $\boldsymbol{4H_2}$**O** = $(\boldsymbol{Ca\ Cl_2, 6H_2O})_{\boldsymbol{aq}}$+ Release of heat **(III.1)**

III.6. Supercooling

Salt hydrates' ability to supercool after freezing poses a significant challenge for their use as phase change materials. Figure III.6 illustrates that cooling a liquid hydrated salt over its melting point ($\boldsymbol{T_m}$) leads to crystallization. The crystallization process proceeds spontaneously when the temperature rises to the melting point. The solution temperature remains constant until the salt solidifies fully. Impurities and PCM container geometry can impact supercooling (Gawron & Schroder, 1977; Abhat, 1983). According to Lane (1983c, p. 119), the pace of cooling has a significant impact on this parameter[40].

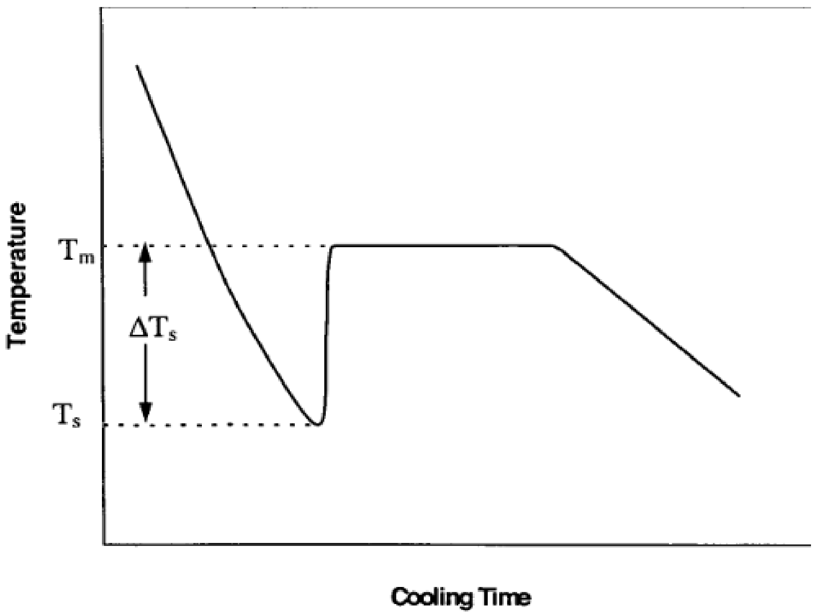


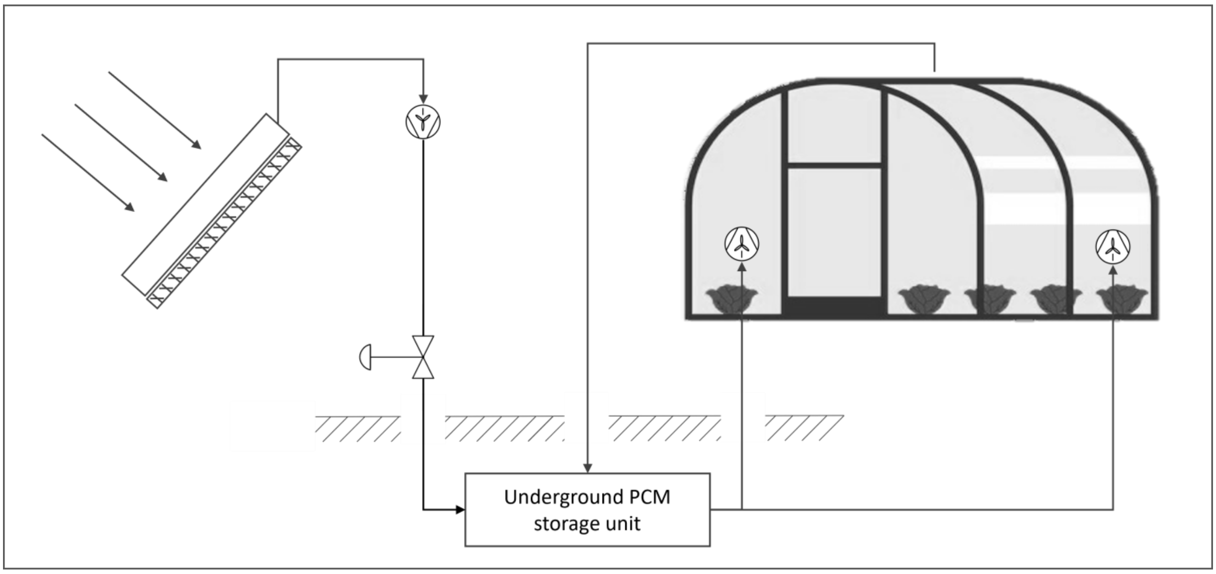
Figure III.6 Freezing behaviour of a solution with a supercooling tendency[40]

III.7. Underground heating system

In this study, the storage system stores thermal energy from the solar air heater during the day and releases it at night to keep the greenhouse temperature stable. The storage method uses a PVC tube, which is both sturdy and cost-effective. The tube is planted 1m underground, providing natural insulation and minimizing heat loss to the environment.

PCM cans, which store thermal energy, are put within the cylindrical tube. PCM, or Phase Change Material, is a material capable of storing significant thermal energy during melting or solidification. The PCM is $\mathbf{Ca}\boldsymbol{Cl_2}\mathbf{,6}\boldsymbol{H_2}\mathbf{O}$, which melts at 29°C and solidifies at 25°C.

The storage system includes fans for charging and draining PCM cans. During the day, fans circulate warm air from the solar air heater into the cylindrical tube, melting the PCM and storing thermal energy. At night, the fans blast frigid air greenhouse into the cylindrical tube, hardening the PCM and releasing thermal energy. A plastic tube with holes is used to disperse heat evenly around the greenhouse. The tube is strung at a height of 0.10 m near the planting, releasing air from the TES. Figure III.7 depicts the solar air heater's dimensions, which are 1.2 m broad and 0.8 m long [4].



.Figure III.7 Schematic diagram of the underground heating system

The heating system is constituted as follows :

- Hot air solar collector .
- Latent thermal energy storage unit [12].

III.7.1. Hot air solar collector

Figure III.8 shows the solar collector, which consists of a single-pass solar absorber and a 5mm thick glass cover. The absorber has an inclined surface and is mounted to a 3 mm thick matte black aluminum profile. Its measurements are 1.2m long and 0.8m wide. Polystyrene is used to provide thermal insulation. A 4cm thick layer of polystyrene is applied on the sides[12].

Figure III.8 Hot air solar collector

III.7.2. Latent thermal energy storage unit LTES

The tank utilized in this investigation is made up of two cylindrical PVC tubes with a diameter of 16 cm and a length of 1.80 meters Figure III.9, filled with 450 gram PCM cans (33cl) Figure III.10. The tubes were put 50 cm below the ground surface in the experimental greenhouse. The lower side of both tubes was perforated to prevent pressure loss and humidity.

A total of 24 PCM cans were allotted and spread between the two tubes. These cans were arranged within the tubes, with each PCM unit around 15 cm away from the next Figure III.11, to enhance the contact surface area between the air and the PCM cans. The output connects to the solar collector at the junction of the two tubes.

Two plastic tubes (60 mm in diameter) with perforations serve as outlets, releasing hot air from the solar collector or tank and distributing it evenly throughout the greenhouse FigureIII.12. The heat distribution system is hanging at a height of 15 cm close to the plants Figure III.13. The inlets connect to the tank outlet, and the other end of the two tubes is closed [12].

Figure III.9 two cylindrical PVC tubes

Figure III.10 PCM cans (33cl)

Figure III.11 PCM cans inside the tubes

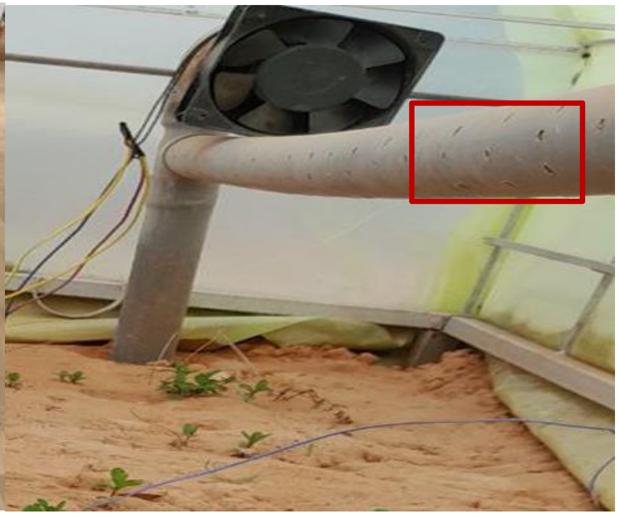


Figure III.12 Perforated tube

Figure III.13 The installation of the two tubes

III.8. The operating principle of the phase change material solar heating system

To improve the efficiency of solar heating, we used calcium chloride hexahydrate ($Ca\,Cl_2, 6H_2O$) as a phase change material (PCM) in an experimental greenhouse, and another similar control greenhouse without any heating system for comparison. Both greenhouses contained mint crops.

The two tubes containing calcium chloride hexahydrate ($\mathbf{Ca\,Cl_2, 6H_2O}$) were placed underground, and the greenhouse structure was installed above them. Twelve temperature sensors were placed in various locations inside and outside the greenhouse.

The solar heating system relies on a solar air collector connected to a thermal energy storage (TES) unit via a pipe with fans to introduce hot air. This system provides proper heating for the greenhouse and is also used to charge the phase change material (PCM), which changes its physical state when absorbing heat and releases it when needed. This process occurs during the day.

In the absence of sunlight and when the temperature drops, the phase change material (PCM) releases its stored heat and distributes it throughout the greenhouse using perforated tubes to ensure effective and adequate thermal distribution for the crops[4].

Table III.3 Temperature Measurements using Thermocouples in the Experimental Setup

Thermocouples	Measure
CH_1	PCM greenhouse temperature
CH_2	Soil temperature in a PCM greenhouse
CH_3	Soil temperature inside the greenhouse without PCM
CH_4	Greenhouse temperature without PCM
CH_5	temperature inlet of cans
CH_6	temperature outlet of cans
CH_7	Temperature at the center of the storage channel
CH_8	Temperature at the outlet of the storage channel
CH_9	absorber temperature
CH_{10}	temperature outlet of the solar collector

III.9. NARX model

The NARX (Nonlinear AutoRegressive model with eXogenous inputs) algorithm is an advanced model used in the field of nonlinear dynamic system modeling, particularly in systems influenced by multiple external factors. This algorithm is based on the principle of predicting future values of a specific time-dependent variable (e.g., the internal temperature of a greenhouse) by relying on previous values of the same variable, in addition to influential external inputs such as outside temperature, humidity, and solar radiation.

NARX is distinguished by its ability to capture complex and nonlinear relationships between variables, making it particularly well-suited for thermal prediction applications in controlled agricultural environments, where multiple overlapping environmental factors affect the thermal system.

The model is implemented through two main phases: the training phase, during which historical data of the system variables and external conditions are used to teach the model how to map the inputs to the system's outputs; and the prediction phase, in which the trained model is used to forecast future temperature values based on live or anticipated input data.

This predictive capability helps improve the thermal system's performance by enabling proactive decision-making regarding climate control operations, such as adjusting heating or ventilation systems. As a result, it enhances temperature stability inside the greenhouse, improves energy efficiency, and promotes optimal conditions for plant growth[41].

The model is mathematically expressed as follows:

$$\mathbf{y(t)=f(y(t-1),y(t-2),...,y(t-n_y);u(t-1),u(t-2),...,u(t-n_u))} \quad \textbf{(III.2)}$$

Where:

- **y(t)** is the output at time **t**.
- **u(t)** represents the external inputs.
- $\mathbf{n_y}$ and $\mathbf{n_u}$ are the respective time delays for outputs and inputs.
- **f** a nonlinear function typically approximated by a neural network.

Table III.4 Evaluation metrics [36][42]

metrics	Equation	Description
MSE	$\frac{1}{n}\sum_{i=1}^{n}(T_{obs\ i} - T_{predict\ i})^2$	The Mean Squared Error (MSE) is a metric that reflects how far predicted values deviate from actual values by averaging the squared differences between them. A lower MSE indicates better predictive model performance. The value is always positive, and values closer to zero are preferred as they represent higher predictive accuracy.
RMSE	$\sqrt{\frac{1}{n}\sum_{i=1}^{n}(T_{obs\ i} - T_{predict\ i})^2}$	The Root Mean Square Error (RMSE) indicates how well a predictive model performs in the short term. It is always a positive number, and lower values—ideally close to zero—suggest better model accuracy.
R^2	$1-\frac{\sum_{i=1}^{n}(T_{obs\ i}-T_{predict\ i})^2}{\sum_{i=1}^{n}(T_{obs\ i}-\overline{T_{obs\ i}})^2}$ $T_{obs\ i}$ **:** The actual (observed) value at point *i* . $T_{predict\ i}$ **:** The predicted value from the model at point *i* . $\overline{T_{obs\ i}}$ **:** The arithmetic mean of the observed values . n **:** The number of data points or observations .	This approach helps assess how accurately the model predicts standardized data. The R^2 value ranges from 0 to 1, with values closer to 1 indicating better model performance .

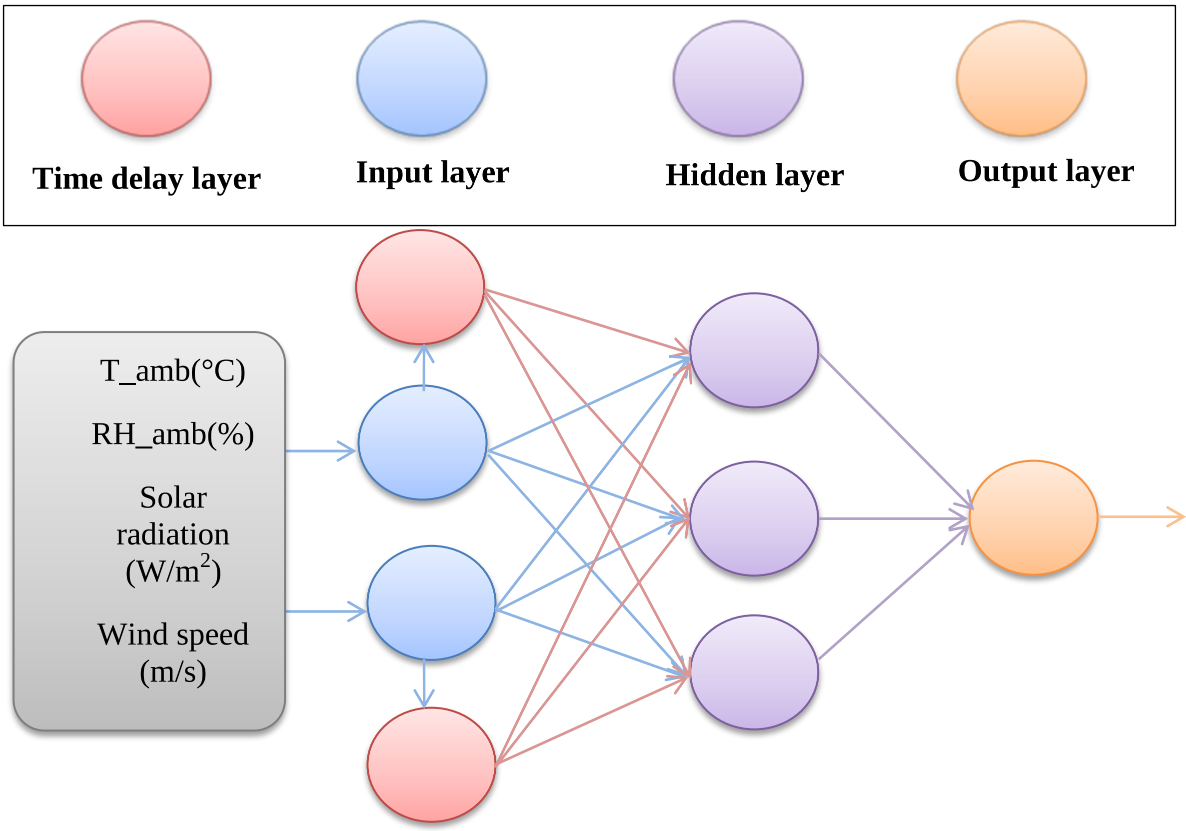


Figure III.14 Structure of NARX model [41]

III.10. Conclusion

This chapter details the instruments and procedures used in this investigation. This includes a description of the methods utilized for choosing and preparing the phase change material (PCM), namely calcium chloride (**$CaCl_2$**), using precise laboratory procedures to enhance the thermal performance of the storage system. Furthermore, the equipment utilized to collect climatic data within the greenhouse was explained, including sensors and measuring devices that supplied accurate temperature and humidity readings.

Furthermore, a simple description of the NARX method (Nonlinear AutoRegressive model with exogenous inputs) was presented, which was used as an excellent prediction tool for estimating the greenhouse's interior temperature. The model was built in stages, beginning with data gathering, progressing to training, and finally testing and assessment. This allowed for precise simulation of the complicated interactions between meteorological and thermal

In the next chapter, we will examine the collected data and analyze the model's performance under various scenarios to determine its usefulness in enhancing temperature control in greenhouses equipped with thermal storage units.

Chapter IV: Results and discussion

IV .1.Introduction

The final chapter of this thesis focuses on the analysis and discussion of the data obtained from the heating system used in the experimental greenhouse. The study was conducted on two greenhouses: one equipped with a heating system that includes a phase change material (PCM), and the other serving as a reference greenhouse for comparison purposes. The aim of this study is to evaluate the performance of the heating system under various climatic conditions through close monitoring of several thermal indicators.

The objective of the experiment was to assess the system's efficiency in maintaining optimal indoor temperatures, with a focus on temperature stability, the difference between indoor and outdoor temperatures, and energy consumption. A set of devices and sensors was used to continuously record data over different time periods.

This chapter presents the experimental results, followed by a detailed analysis that demonstrates the system’s success in providing a thermally suitable environment for plant growth. It also addresses the operational strengths and challenges encountered during use, along with an economic analysis of energy consumption in relation to the achieved thermal performance.

In conclusion, this study aims to provide a clear perspective on the potential for improving the performance of heating systems in greenhouses located in arid regions, with an emphasis on achieving a balance between operational efficiency and energy cost.

IV .2.Experimental Periods and Testing Conditions

The experimental experiments were carried out to assess the thermal performance of an agricultural greenhouse equipped with Phase Change Material (PCM) during two independent time periods, ensuring result dependability and reproducibility under varying climatic circumstances. The first period lasted from January 27 to February 2, and was marked by relatively cold weather with large temperature differences between day and night. This provided a favorable background for evaluating the PCM's ability to collect and store thermal energy throughout the day before gradually releasing it at night.

The second phase, from March 4 to March 9, saw gentler conditions with the commencement of rising temperatures, allowing for an assessment of the system's response in a new thermal regime. Temperature measurements were taken inside the greenhouse during both periods under two conditions: with and without PCM, as well as ambient (outside) temperature, to allow for comparative analysis and to determine the effectiveness of PCM in improving thermal stability within the greenhouse.

IV .3.Thermal Performance Analysis of the Solar Collector During the Experiment Period

Our experiment began at 2:00 PM on January 27 and ended at 3:00 PM on February 2. (Figure IV .1) during this period , the peak of global solar radiation exceeded 700 W/m², while the lowest reported figure decreased to -2 W/m², possibly during twilight hours. The solar collector's temperature ranged from about 80 °C to a low of 6 °C. These numbers represent the direct impact of solar radiation on the collector's thermal behavior, with high radiation levels contributing to higher absorber temperatures during the day and large reductions in both parameters at night.

This data verifies the recognized relationship between solar radiation and the thermal performance of the solar system, delivering vital insight into its behavior under different environmental conditions.

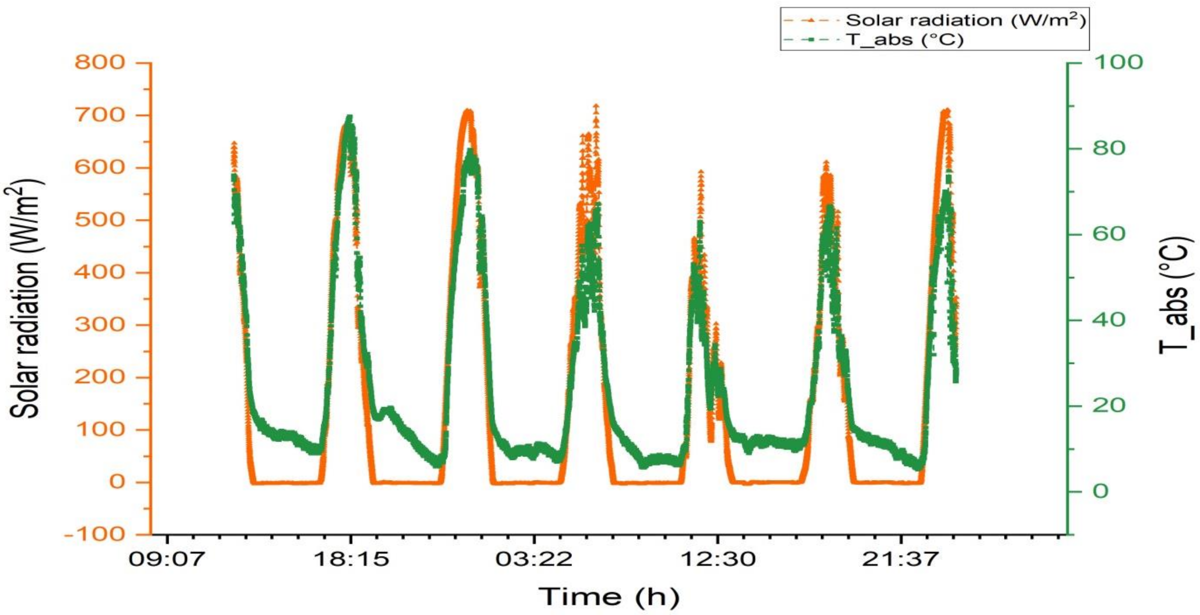


Figure IV .1 Relationship Between Global Solar Radiation and solar collector's temperature

IV .4. Analysis of Experimental Results of Greenhouse Temperature Variations

The graph (Figure IV.2) shows temperature variations within an agricultural greenhouse from January 27 to February **2**, with measurements taken under three conditions: with Phase Change Material (PCM), without PCM, and at ambient (outside) temperature. After studying the curve, it is clear that thermal variations were more dramatic in the absence of PCM, with peak temperatures exceeding 32°C during the day and dipping below 10°C at night, resulting in a daily thermal swing that might exceed 22°C.

When PCM was employed, however, these variations were greatly decreased; peak temperatures did not surpass 30°C, and overnight lows rose to around 12°C, indicating a reduced thermal swing of approximately 17-18°C. This amounts to a 20-25% improvement in thermal stability. This effect is due to the PCM's ability to absorb excess heat during the day by melting and gradually release it at night via solidification, resulting in a more balanced thermal environment within the greenhouse.

The graph also reveals that the ambient temperature fluctuated significantly more, and the temperature difference between the interior and outside increased with the presence of PCM. This confirms PCM's usefulness as a dynamic thermal barrier, which improves the system's overall energy efficiency.

As a result, the findings show that incorporating PCM into solar heating systems for greenhouses is a viable technique for guaranteeing consistent indoor climatic conditions and optimal plant growth throughout the day.

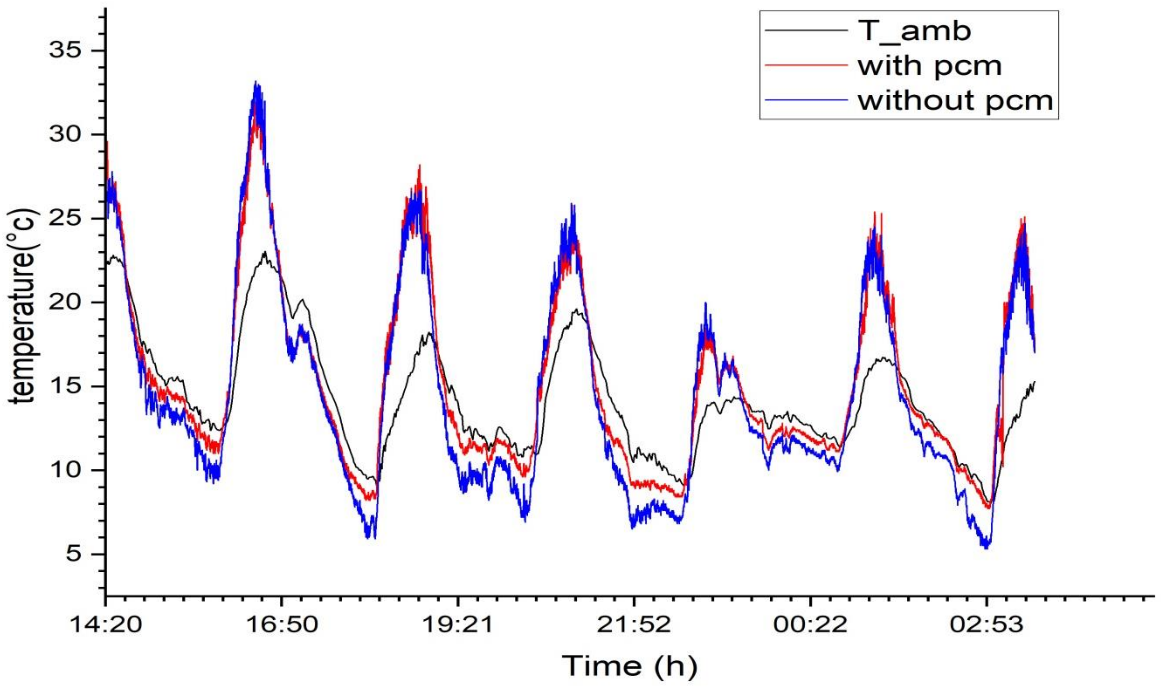


Figure IV .2 Temperature variations of the two greenhouses during the period from .January 27 to February 2, 2025, using Phase Change Material

Significant variations in the environmental parameters under study were observed between January 27 and February 2, 2025, indicating mild atmospheric fluctuations typical of this time of year. Outdoor temperatures ranged from a low of 8°C to a high of 20°C, suggesting distinct daily thermal changes caused by intense solar radiation throughout the day and naturally lower nighttime circumstances. Relative humidity varied greatly between 20% and 80%, indicating the passage of various air masses, with lower humidity levels being associated with dry, sunny days. Solar radiation peaked at 700 W/m², while the smallest recorded value was around -2 W/m² (Figure IV .3), indicating a pattern of totally sunny days and overcast or dark periods with minimal radiation. These changes demonstrate the dynamic interaction of temperature, humidity,and solar radiation, which has a direct impact on thermal comfort and energy system performance.

Wind speeds ranged from 0.06 to 8 m/s during the observation period (Figure IV.4). Calm conditions, with nearly stagnant air, contributed to moisture collection and impeded natural ventilation, which could have an impact on thermal sensation and interior air quality. Stronger winds, on the other hand, increased natural ventilation and convective heat exchange, assisting in the regulation of temperature conditions. These variations in wind behavior highlight its independent but considerable role in determining environmental comfort and the performance of passive or hybrid energy systems.

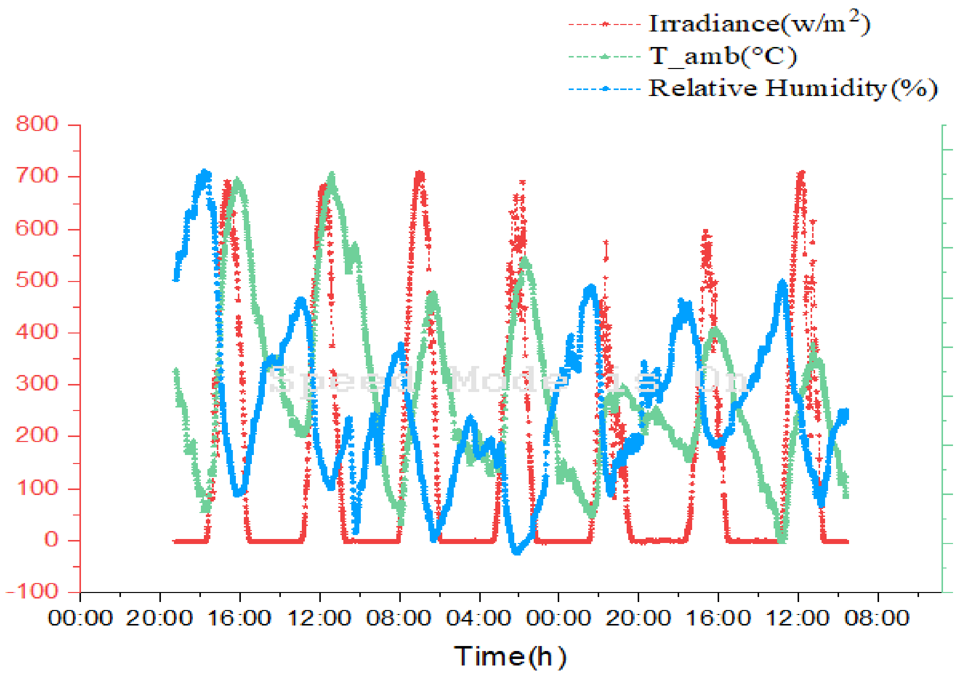


Figure IV .3 Evolution of ambient temperature, humidity, and radiation during the experiment days

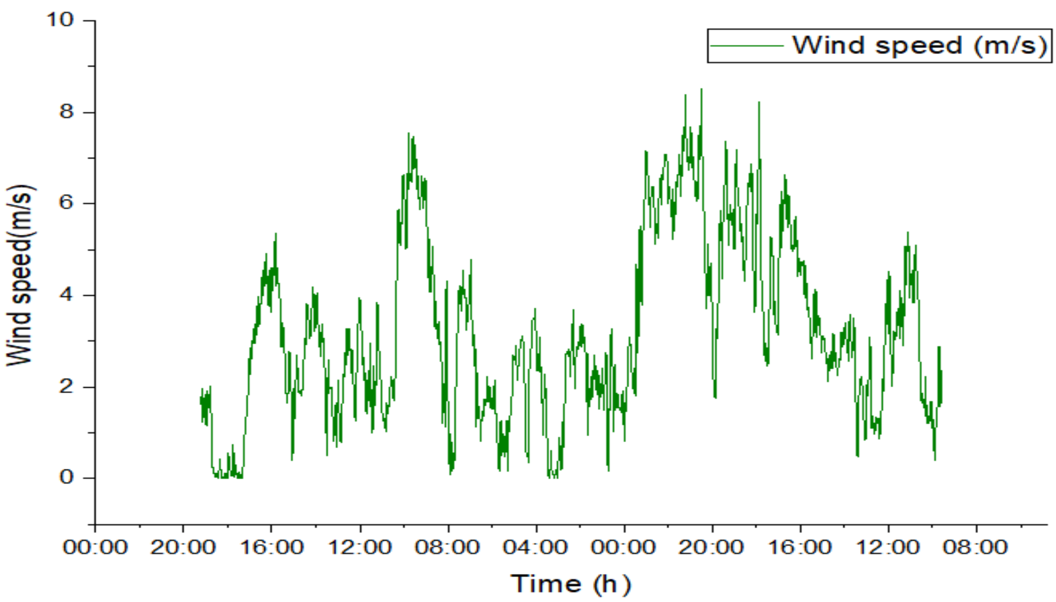


Figure IV .4 Wind speed variations during the experiment days

After reviewing the results of the first period, which was characterized by cold weather and significant thermal fluctuations between day and night, we now move on to analyze the results of the second experiment conducted under milder climatic conditions from

March 4 to March 9 . This phase aims to evaluate the thermal performance of the greenhouse system under different thermal regimes by comparing internal temperatures with and without the use of Phase Change Material (PCM), while also considering variations in external ambient temperature. Temperature analysis during the experimental period reveals a clear difference between the condition without PCM and the condition with PCM (Figure IV.**5**). In the greenhouse without PCM, the maximum temperature reached 33°C, with a minimum temperature of 8°C. In contrast, the greenhouse equipped with PCM showed a reduced maximum temperature of 29°C and an increased minimum temperature of 10°C. This variation reflects the effect of PCM in reducing thermal fluctuations within the greenhouse, contributing to improved thermal stability and a decreased daily temperature range between highs and lows. This analysis provides deeper insight into the PCM's responsiveness to changing environmental conditions and its effectiveness in enhancing thermal stability during transitional periods of the year.

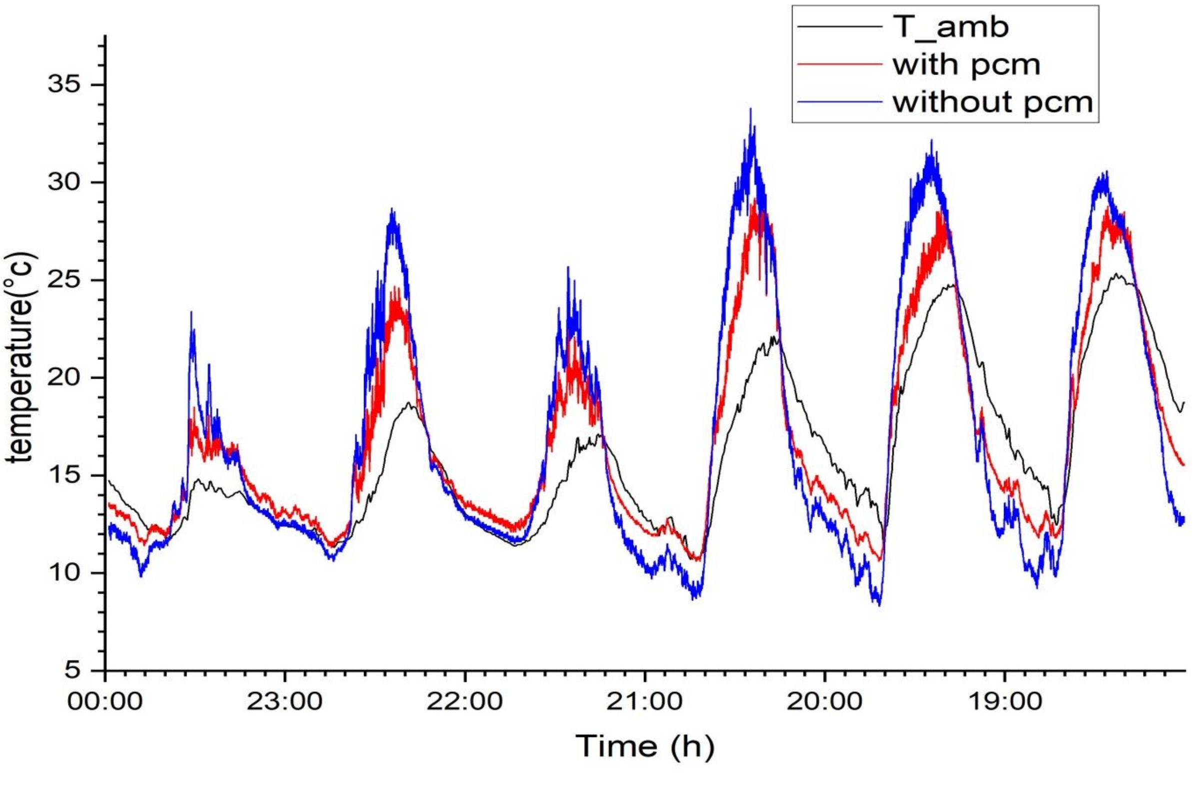


Figure IV .5 Temperature variations of the two greenhouses during the period from March 4 to March 9, 2025, using Phase Change Material

The graph (Figure IV.6) depicts regular variations in the analyzed meteorological parameters, indicating relative stability in weather conditions. The solar irradiance data follows a daily pattern, gradually increasing after sunrise, peaking between 12:00 PM and

2:00 PM with levels surpassing 800 W/m², and then decreasing to zero at sunset. This consistent pattern suggests largely bright days with minor changes at the top, which could be related to the passing of light clouds.

The ambient temperature rises on a daily basis, according to the increase in sun irradiation. Maximum temperatures varied from 22°C to 26°C, while overnight lows fell below 12°C, showing a daily thermal differential of almost 14°C on certain days. This difference is deemed modest and has a direct impact on the performance of thermal systems like greenhouses and solar collectors.

In contrast, relative humidity followed an inverse pattern to temperature. It peaked in the early morning (between 90% and 100%) because to low temperatures, then decreased dramatically over the day to approximately 30% or less as temperatures rose. This significant daily change in humidity reflects the effect of solar heating on air mass and validates the well-known inverse link between temperature and relative humidity.

Overall, the data during this period indicates a transitional climate between winter and spring, giving a perfect condition for evaluating the performance of thermal systems employing Phase Change Materials (PCM).

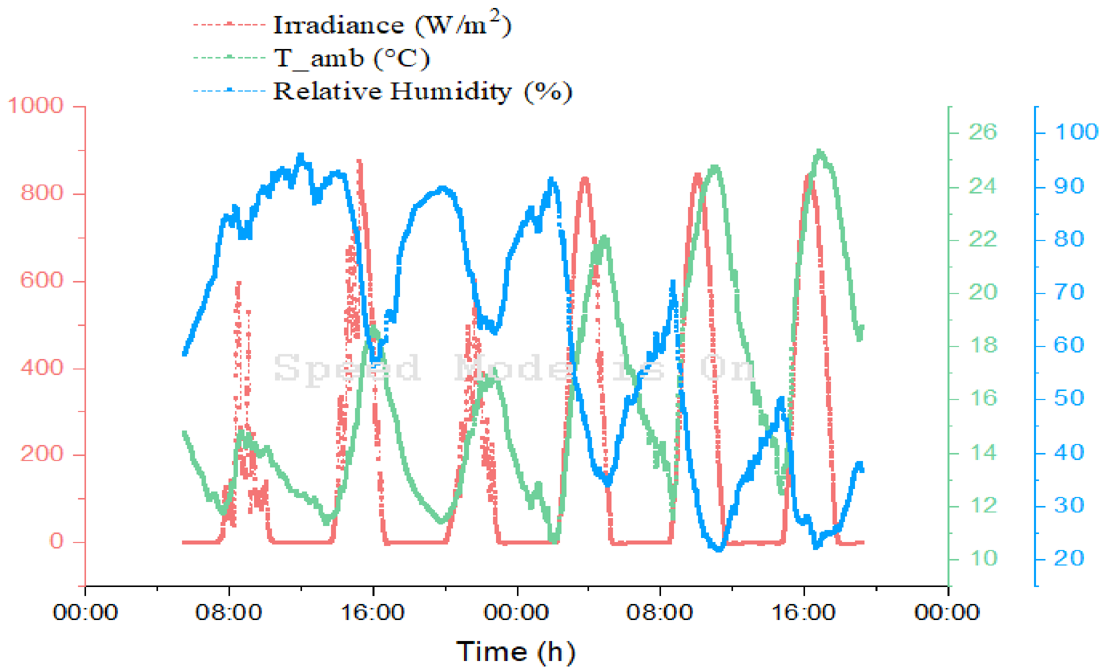


Figure IV .6 Evolution of ambient temperature, humidity, and radiation during the experiment days

IV .5. Enhancing Thermal Storage Efficiency in Greenhouses Using Dual Phase Change Material (PCM) Systems (Subsurface and Surface)

From May 13 to May 18, 2025, a fresh thermal experiment was carried out within an agricultural greenhouse that had been outfitted with 20 Phase Change Material (PCM) containers positioned above ground level (Figure IV.7).

The comparative graph (Figure IV.8) clearly demonstrates that the greenhouse with PCM had much lower daytime temperatures, not reaching 35-37°C, whilst the greenhouse without PCM had temperatures above 40°C. This difference is due to the PCM's capacity to absorb a significant amount of heat during the day, lowering thermal stress within the greenhouse. The progressive release of stored heat throughout the solidification process allowed the PCM-equipped greenhouse to sustain higher temperatures at night, limiting the dramatic overnight temperature reductions.

In comparison, the daily thermal fluctuation in the greenhouse without PCM varied between 17 and 25°C, but it reduced to roughly 12-18°C in the PCM-equipped greenhouse, indicating a 20% to 30% improvement in temperature stability. These findings demonstrate that placing PCM containers above ground improves thermal regulation and creates a more balanced internal environment in greenhouses during warm transitional periods, confirming the technique's viability in improving agricultural system performance.

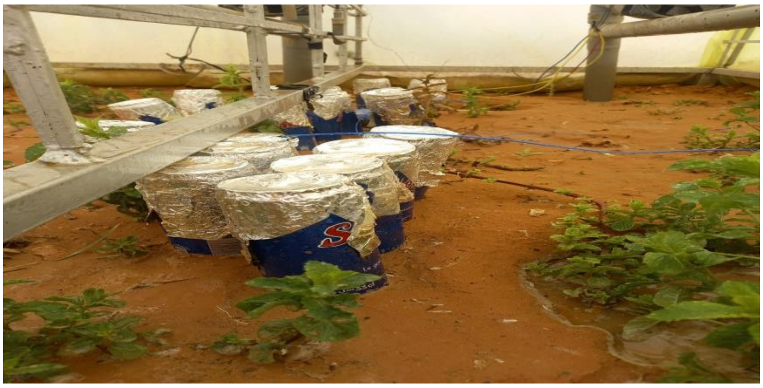


Figure IV.7 PCM containers above ground level

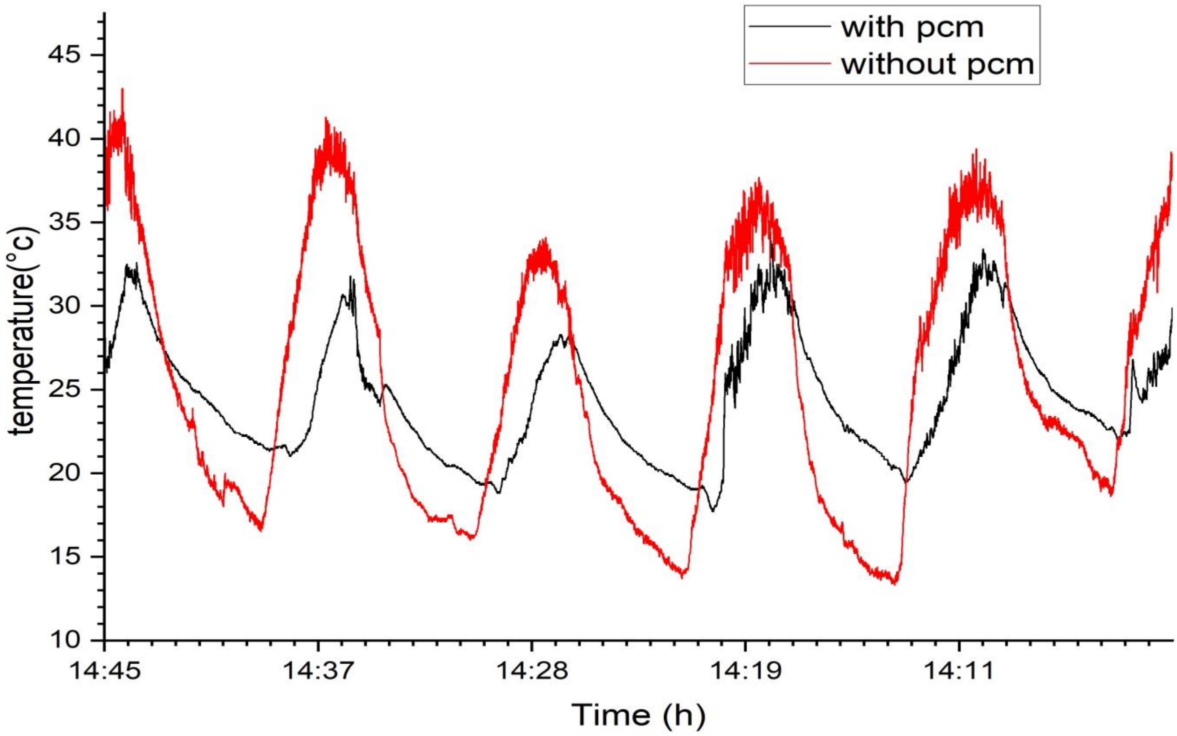


Figure IV.8 Thermal Performance of a Greenhouse Equipped with Subsurface and Surface Thermal Storage Systems Compared to a Reference Greenhouse

IV .6. Artificial Neural Network prediction

This study sought to investigate the impact of controlled environment on plant physiological health, particularly in shifting climatic conditions that may impede development during hot seasons.The NARX artificial neural network model was used to estimate the temperature inside a greenhouse using a phase change material (PCM) thermal energy storage unit.

Environmental data from inside the greenhouse were collected over five days in March 2025 to train the model(Figure IV.9).The data comprised temperature measurements taken inside the greenhouse.

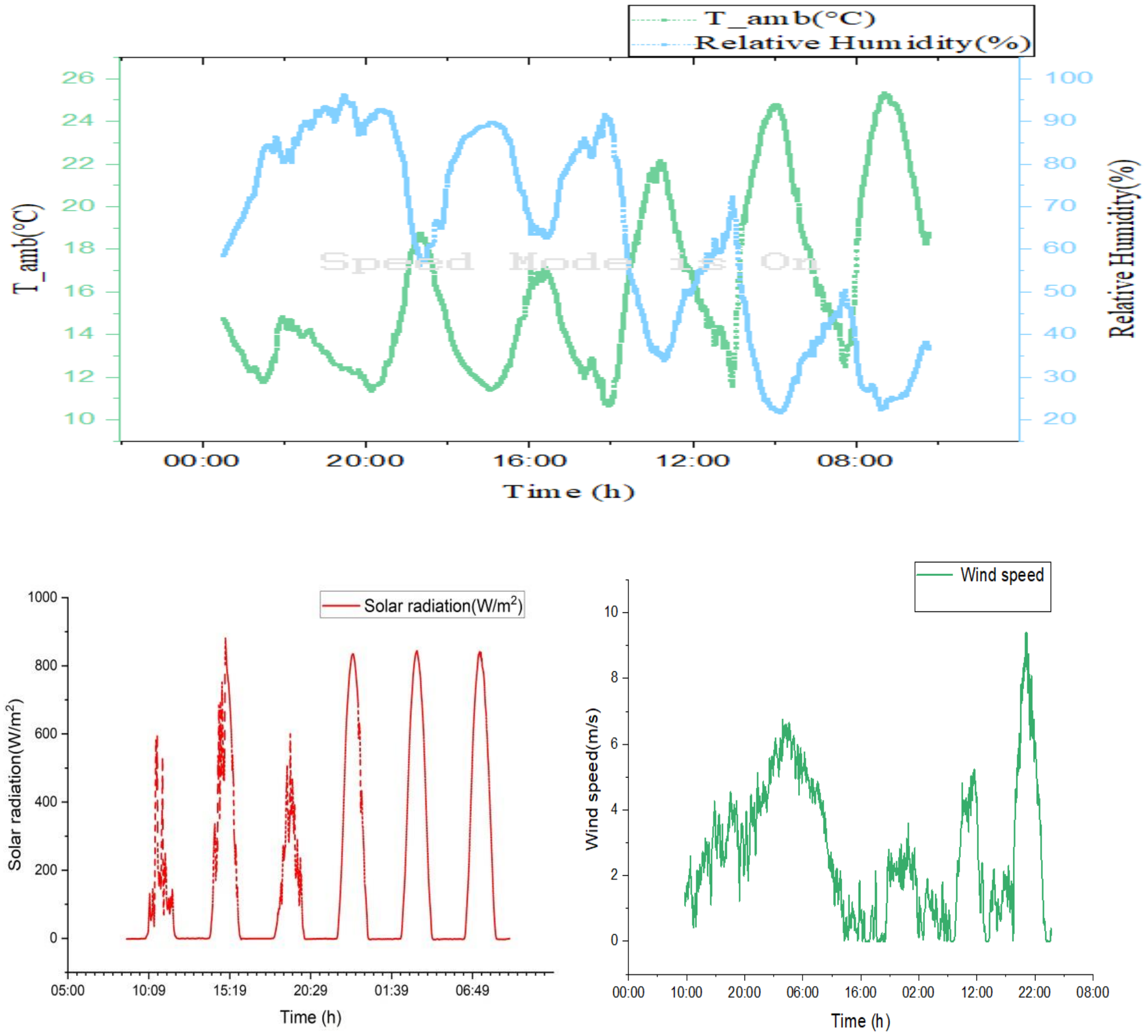


Figure IV.9 Various ANNs model inputs (ambient temperature and humidity, solar irradiation,wind velocity)

The model was trained until an acceptable low root mean square error (RMSE) was obtained. The model's performance was assessed using two key metrics: coefficient of determination R^2, RMSE, and mean squared error (MSE).

The coefficient of determination (R^2 = 0.9853) shows a significant correlation between actual and anticipated temperature readings inside the greenhouse. The (RMSE = 0.640), and the (MSE =0.431) Table VI.1 , indicating great accuracy in temperature prediction.

Table IV.1 validation model

	R^2	RMSE	MSE
NARX	0.9853	0.640	0.431

These findings demonstrate that the NARX model has good predictive performance and may be used to control temperature inside greenhouses equipped with PCM units, providing ideal climatic conditions for plant physiological growth.

This study emphasizes the potential use of artificial neural network (ANN) models to improve greenhouse thermal efficiency in real-world settings and contributes to the trend of smart agriculture based on artificial intelligence technologies. The results were also graphically depicted with Python (Figure IV.10).

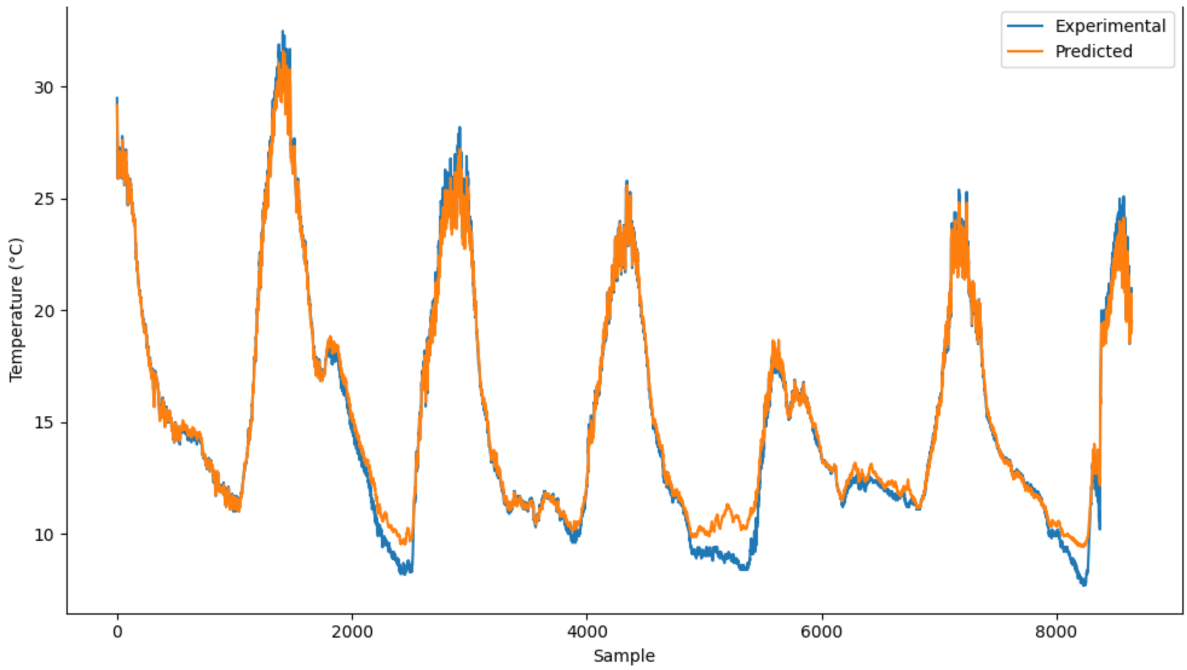


Figure IV.10 Output of ANN model NARX with LTES

IV.7. Conclusion

In this chapter, we studied and discussed the findings from tests carried out on agricultural greenhouses under various climatic circumstances. Environmental variables such as exterior temperature, relative humidity, sun radiation, and wind speed were visually depicted. Two greenhouses were compared during two separate time periods: days in January and days in March. One had a phase change material (PCM) placed beneath, whereas the other did not.

The findings indicated the usefulness of PCM in managing the greenhouse's interior climate, which improved plant growth conditions. When extra PCM was introduced above ground in a greenhouse that already had PCM underground, we saw improved thermal performance since the material contributed to nocturnal heating and daytime cooling, demonstrating its dynamic thermal storage and release characteristics.

In addition, a NARX artificial neural network model was employed to forecast interior temperature. The model proved to be quite effective, with accurate forecasting capabilities, indicating its potential use in intelligent temperature management systems for greenhouses.

Overall, these findings emphasize the necessity of adopting phase change materials (PCMs) as an effective approach for improving greenhouse energy performance. When integrated with artificial intelligence approaches such as neural networks, this approach shows promise for constructing smart and sustainable agricultural systems that can adjust to climate fluctuation and resource constraints.

General Conclusion

General Conclusion

In conclusion, this thesis addressed the concept of agricultural greenhouses and their historical development, with an overview of their types and the climatic factors influencing their performance. Various methods used to control these factors were examined, particularly solar-powered heating systems and the use of effective materials to enhance agricultural production.

A significant part of the study focused on reviewing previous research on the use of phase change materials (PCMs) in greenhouses. These materials have proven to be highly effective in thermal storage systems due to their ability to melt and solidify at specific temperatures. In addition to being environmentally friendly and cost-effective, PCMs have become an increasingly reliable solution for farmers to improve crop quality and extend growing seasons.

The experiments for this research were conducted at the Applied Research Unit for Renewable Energies in Ghardaïa, where calcium chloride (**$CaCl_2$**) was selected as the PCM. It was prepared using precise laboratory procedures aimed at enhancing the thermal performance of the storage system. Advanced sensors and measuring devices were also used to collect accurate climatic data inside the greenhouses.

Furthermore, the NARX neural network model (Nonlinear AutoRegressive model with exogenous inputs) was employed as an effective predictive tool for estimating internal greenhouse temperatures. The model was developed through stages of data collection, training, testing, and evaluation, which enabled accurate simulation of the complex interactions between meteorological and thermal variables.

The results of experiments conducted under different climatic conditions confirmed the effectiveness of using PCM. A comparison between two greenhouses—one equipped with PCM and the other without—showed that PCM significantly improved the internal climate and enhanced plant growth conditions(Figure 1). Additionally, using PCM both underground and above ground improved thermal performance, especially by storing heat at night and releasing it during the day.

Figure a) Plant growth with PCM b) Plant growth without PCM

The **NARX** model also demonstrated high accuracy in predicting internal temperatures, showing great potential for integration into intelligent climate management systems in future greenhouse designs. These results emphasize the importance of moving toward smarter and more sustainable agricultural systems.

Despite these positive outcomes, several field challenges were encountered during the research, including:

- Intermittent data recording due to sensor malfunctions or connectivity issues.
- Sudden power outages, especially at night, which led to partial data loss.
- The need for regular equipment maintenance to ensure consistent and accurate data collection.

Nonetheless, the study was successfully completed, and its primary objectives were achieved, providing a solid foundation for future development.

In light of this, we propose several ideas to further develop this work:

1. Integrating Internet of Things (IoT) technologies to build a smart sensor network capable of real-time data collection and cloud-based storage to prevent data loss.
2. Using independent renewable energy sources, such as solar panels with battery storage, to ensure continuous operation during power outages.
3. Enhancing predictive models by incorporating more advanced algorithms like LSTM or GRU to improve climate forecasting accuracy.

4. Testing new or composite PCM materials with improved thermal properties that are better suited to local climatic conditions.
5. Developing a dedicated digital platform for farmers to remotely monitor greenhouse performance and receive automated alerts and recommendations for optimal thermal control.

These future directions represent a genuine opportunity to transition toward intelligent and sustainable agricultural systems capable of adapting to climate change and environmental challenges—contributing to improved productivity and greater food security through the use of renewable energy and modern technologies.

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Département des Enseignements Communs en Sciences et de la Technologie | Université de Ghardaïa | قسم التعليم المشترك في العلوم والتكنولوجيا

غرداية في : 2025/06/28

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الإذن بطباعة النسخة النهائية لمذكرة ماستر الموسومة بعنوان

Study and modeling of the thermal behavior of a greenhouse heated by solar energy using PCM

مضاء رئيس القسم

رئيس قسم التعليم المشترك في العلوم والتكنولوجيا
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جامعة غرداية - كلية العلوم و التكنولوجيا - قسم التعليم المشترك في العلوم و التكنولوجيا