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Implementation of HVAC systems to manage the greenhouse climate

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B. Abdelbasset, R. M.Erregani

Dedication

I dedicate this humble dedication to my beloved parents, whose love, encouragement, and tireless sacrifices have created a warm and nurturing environment for my academic success. hoping that I can make you proud.

To my brothers and sisters, you are my family and closest friends. Your unwavering support has been a source of inspiration and strength for me. I am deeply grateful to you.

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To all of you, I dedicate this dedication with deep respect, sincere appreciation, and infinite feelings of love and gratitude.

Sincerely,

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In the name of Allah, I offer this heartfelt tribute to my esteemed parents, whose unwavering support has been instrumental in bringing us to this point.

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Abstract

The increasing global population, coupled with challenges arising from climate change and water scarcity, leads to a heightened vulnerability of food supplies, particularly in advanced countries. Hence, a crucial goal in the coming years will be to enhance crop productivity. Intensive horticulture is poised to play a pivotal role in meeting the rising demand for food. However, in the specific context of greenhouse cultivation, relying solely on passive control of environmental conditions proves insufficient. Consequently, the adoption of active heating/cooling systems becomes imperative.

In this study, we conducted an experimental investigation on a double-span greenhouse in a semi-arid region. heating and cooling systems were developed to manage the local climate within the greenhouse. A novel system was designed, and manufactured for solar latent thermal energy storage (LTES) to provide greenhouse heating during the winter, alongside implementing natural ventilation, shading systeme, and employing a second cooling system FAN-PAD system incorporating palm fiber materials to cool the greenhouse during the summer. Our evaluation demonstrates the exceptional efficiency of these integrated systems in effectively controlling the greenhouse climate while maintaining environmental sustainability. The results provide strong evidence for the practical application and effectiveness of this approach in addressing the intricate interplay between greenhouse temperature control and environmental sustainability.

KEY WORDS: Greenhouse, heating systems, FAN-PAD system, latent thermal energy storage (LTES), shading systeme, Temperature.

Résumé:

La croissance de la population mondiale, associée aux défis posés par le changement climatique et la rareté de l'eau, entraîne une vulnérabilité accrue des approvisionnements alimentaires, notamment dans les pays avancés. Par conséquent, l'amélioration de la productivité des cultures constitue un objectif crucial dans les années à venir. L'horticulture intensive est appelée à jouer un rôle essentiel pour répondre à la demande croissante en nourriture. Cependant, dans le contexte spécifique de la culture en serre, il est insuffisant de compter uniquement sur le contrôle passif des conditions environnementales. Par conséquent, l'adoption de systèmes actifs de chauffage/refroidissement devient impérative.

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Dans cette étude, nous avons mené une investigation expérimentale dans une serre à double paroi située dans une région semi-aride. Des systèmes de chauffage et de refroidissement ont été développés pour gérer le climat local à l'intérieur de la serre. Un nouveau système de stockage d'énergie thermique latente (LTES) a été conçu et fabriqué pour assurer le chauffage de la serre pendant l'hiver, en plus de la mise en œuvre d'une ventilation naturelle, d'un système d'ombrage et de l'utilisation d'un deuxième système de refroidissement, le système FAN-PAD, incorporant des matériaux à base de fibres de palmier pour refroidir la serre pendant l'été. Notre évaluation démontre l'efficacité exceptionnelle de ces systèmes intégrés pour contrôler efficacement le climat de la serre tout en préservant la durabilité environnementale. Les résultats fournissent des preuves solides de l'application pratique et de l'efficacité de cette approche dans le traitement de l'interaction complexe entre le contrôle de la température de la serre et la durabilité environnementale.

Mots-clés: serres, systèmes de chauffage, stockage d'énergie thermique latente (LTES), système d'ombrage, température, système FAN-PAD.

ملخص

نمو السكان العالمي، جنبًا إلى جنب مع التحديات التي يواجهها تغير المناخ وندرة المياه، سيزيد من ضعف إمدادات الغذاء، لا سيما في الدول المتقدمة. وبالتالي، سيكون تعزيز إنتاجية المحاصيل أحد التحديات الرئيسية التي يجب معالجتها في السنوات المقبلة. تلعب الزراعة الشديدة التحصيل دورًا حاسمًا في تلبية الطلب المتزايد على الغذاء. في سياق زراعة البيوت البلاستيكية في المناخات المتوسطية، يعتبر الاعتماد فقط على التحكم السلبي في ظروف المحيط غير كافٍ، مما يستدعي استخدام أنظمة التدفئة والتبريد النشطة.

في هذه الدراسة، أجرينا تحقيقًا تجريبيًا في دفيئة ذات ثنائي الانتشار في منطقة شبه قاحلة. تم تطوير أنظمة تدفئة وتبريد لإدارة المناخ المحلي داخل الدفيئة. تم تصميم وتصنيع نظام جديد لتخزين الطاقة الحرارية الكامنة (LTES) لتوفير التدفئة للدفيئة خلال فصل الشتاء، بالإضافة إلى تنفيذ التهوية الطبيعية ونظام التظليل، واستخدام نظام تبريد ثانوي يتضمن نظام FAN-PAD واستخدام مواد ألياف النخيل لتبريد الدفيئة خلال فصل الصيف. توضح تقييماتنا الكفاءة الاستثنائية لهذه الأنظمة المتكاملة في التحكم الفعال في مناخ الدفيئة مع الحفاظ على الاستدامة البيئية. تقدم النتائج أدلة قوية على التطبيق العملي وفعالية هذا النهج في معالجة التفاعل المعقد بين التحكم في درجة حرارة الدفيئة والاستدامة البيئية.

كلمات مفتاحية: البيوت البلاستيكية، أنظمة التدفئة، نظام تخزين الطاقة الحرارية الكامنة (LTES)، ونظام التظليل، درجة الحرارة، نظام FAN-PAD.

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General Introduction

General Introduction

Nowadays, global food production and agriculture face numerous challenges such as the projected global population reaching 9.6 billion by 2050 [1], urbanization, limited arable land, and climate change-induced weather extremes. Consequently, it is crucial to employ new horticultural research technology to enhance future efficiency and production, improve nutrition, ensure food security, and address crises like COVID-19. Advancements in greenhouse technologies have paved the way for science-based solutions in optimizing plant production by managing climate factors such as temperature, light intensity, humidity, and CO_2 concentration. Overall, greenhouses offer a versatile and effective solution for overcoming climate limitations and ensuring year-round crop production. However, greenhouses consume significant amounts of energy compared to other agricultural practices, making energy reduction in agricultural greenhouses a vital target for sustainable industrial development. Automatic greenhouse systems, equipped with a wide array of sensors and actuators, provide monitoring and control capabilities without human intervention. Researchers have been focusing on greenhouse management technology to achieve cost reduction and energy efficiency [2]. Additionally, studies have examined design trends, climate management systems, and indoor climate requirements for agricultural greenhouses including challenging environments such as harsh climates, arid regions, hot regions, tropical areas, and urban settings [3, 4]. Notably, energy-saving techniques and modeling have been explored [5], and advancements in modern sustainable greenhouse cultivation for precision agriculture have been a significant trend [6].

Addressing food vulnerability is a primary challenge in the coming years due to the expected increase in the world population, climate change, and water scarcity, which negatively impact crop productivity. Intensive horticulture plays a crucial role in meeting the growing demand for food with high productivity compared to conventional crops. The horticultural sector in European Mediterranean areas faces competitiveness issues due to market liberalization. This necessitates the development of production systems that ensure high productivity and quality. Additionally, achieving environmentally sustainable food security (availability, access, stability, and utilization) in a low-emission world poses a significant challenge. Intensive horticulture is pivotal in supplying food efficiently and plays a fundamental role in comparison to other production systems.

Furthermore, Mediterranean climate conditions pose obstacles to year-round cultivation. Passive greenhouses, relying on natural ventilation and shading for cooling, can only maintain an appropriate internal microclimate when the external temperature and humidity conditions fall within the favorable range (12 to 29 °C temperature and 50 to 90% relative humidity [7]) for most commonly cultivated greenhouse species. However, this can occur during limited periods of the year in hot and warm regions. Therefore, the implementation of a cooling system capable of reducing greenhouse temperature while maintaining optimal humidity levels becomes essential for ensuring year-round quality food production.

In Algeria, agricultural land occupies only 3.4% of the total area, and only 25% of groundwater resources in the southern regions are currently utilized. The arid climate in the south poses significant challenges to agricultural exploitation, leading to soil infertility, fragility, and nutrient deficiencies. Furthermore, frequent dry and hot winds cause substantial damage to agriculture in southern regions. Greenhouses offer a potential solution to address these challenges [8]. Carefully designed greenhouses effectively manage crucial aspects of agricultural growth by controlling environmental factors such as temperature, humidity, and light, creating optimal conditions for crop production. By utilizing greenhouses, it becomes possible to cultivate crops in climates and seasons where natural growth would otherwise be impossible. However, greenhouses consume a significant amount of energy compared to other agricultural practices. Therefore, reducing energy consumption in agricultural greenhouses is a crucial objective for sustainable industrial development. Implementing energy-efficient techniques, such as automatic greenhouse systems, can reduce the need for human intervention in greenhouse management. Traditional greenhouses heavily rely on fossil fuels, resulting in substantial greenhouse gas emissions. To mitigate this environmental impact and transition to more sustainable practices, integrating renewable energy sources, particularly solar energy, into agricultural greenhouses has shown promise. This integration offers the potential to replace traditional energy sources, reduce greenhouse gas emissions, and enhance overall greenhouse sustainability [1].

As part of our master's study in renewable energies, we have embarked on expanding and enhancing a project initiated by Dr. Ahmed BADJI last year. This project focuses on implementing HVAC (heating, ventilation, and air conditioning) systems in greenhouse climate management.

To achieve our goal, we initially familiarized ourselves with fundamental aspects of greenhouse architecture, location considerations, climate factors, and various types of covering materials. This knowledge provided a solid foundation for our research. We then conducted an extensive literature review to gain a comprehensive understanding of how HVAC systems can be effectively integrated into greenhouse climate management practices. Equipped with insights garnered from our research, we proceeded to the development and testing phase of the project. This involved designing and implementing HVAC systems tailored to greenhouse environments, with a focus on optimizing heating, ventilation, and air conditioning mechanisms.

This thesis consists of four main chapters:

- Chapter I provides an in-depth exploration of agricultural greenhouses, covering topics such as microclimate, shapes and classification, geometry and dimensions, frame and cladding materials.
- Chapter II offers an overview of heating and cooling methods in recent years, presenting various applications.
- Chapter III provides a detailed description of the different systems implemented and tested in this project, including solar heating system, natural ventilation system, shading system, and evaporative cooling fan pad system. The chapter also discusses the thermal analysis of the greenhouse, the instruments and fixtures used for data collection.
- Chapter IV presents the results obtained from the experimental tests conducted inside the greenhouse.

Chapter I : Generality of greenhouse

I.1 Introduction

Greenhouse technology enables farmers to grow crops at a high profit. Additionally, it enables people to purchase almost any fruit or vegetable from their neighborhood market anytime, even if it is out of season. Global crop production increased thanks to the popularity of greenhouse farming methods, which also helped ease world hunger. However, to meet the demands for crop production and quality, the success of greenhouse crop production depends on the ability to control the microclimate inside the greenhouse precisely. In addition, the shape, size, orientation, height, the opening of side and roof vents, wind direction outside the greenhouse, and characteristics of the greenhouse covering material all play significant roles in influencing the microclimate of the greenhouse. [9]

I.2 Definition of greenhouse:

A greenhouse is a structure that is typically enclosed or partially open, made of translucent materials such as glass or plastic, and supported by a frame usually made of metal or wood. The purpose of a greenhouse is to create a controlled and protected environment for the cultivation of crops, ornamental plants, vegetables, or fruit plants. By providing a sheltered space, a greenhouse allows for the establishment of conditions that are somewhat independent or more specific compared to the open outdoor environment [10]. This controlled environment offers advantages such as protection from extreme weather conditions, pests, and diseases, as well as the ability to regulate temperature, humidity, and light levels. Greenhouses are frequently utilized for experimental or educational purposes, where researchers and learners can study plant growth, test new techniques, or gain practical knowledge about horticulture.

The greenhouse environment is influenced by various factors, such as the type and characteristics of the cladding material, air conditioning, greenhouse structure (including design, orientation, and size)

I.3 Microclimate of greenhouse

The critical climatic factors to be considered for open-air and protected cultivation of plants are: (i) solar radiation intensity; (ii) High and low temperature (T); (iii) High and low relative humidity (RH); (iv) Carbon dioxide (CO_2) concentration. By controlling and regulating these parameters, the growing conditions for the crop, as well as valuable energy savings and water use regulation.

I.3.1 Solar Radiation

The solar radiation conditions within a greenhouse play a vital role in production, not only in terms of quantity but also quality. One of the initial changes that occur in the microclimate parameters inside the greenhouse is a reduction in available solar radiation (as shown in Figure I-1). Furthermore, the radiometric properties of the greenhouse cover can significantly alter the quality of radiation, including its distribution spectrum and the proportion of diffuse radiation. These modifications have implications for crops, affecting their radiation utilization efficiency and photomorphogenic effects, as well as impacting insects and microorganisms present in the greenhouse. [11] For the best growth of the cucumber plant in a naturally ventilated greenhouse, solar radiation of 100.0-169 $\mathrm{W \cdot m^{-2}}$has been recommended. [12]

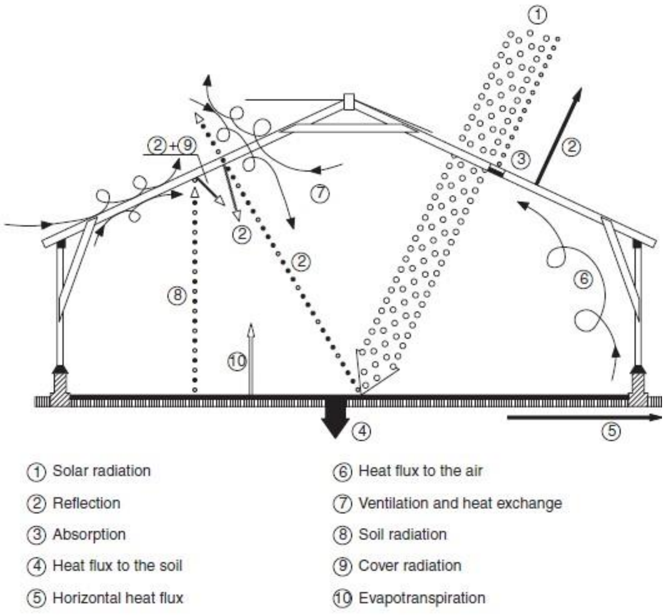


Figure I-1 Radiation and energy balance in a greenhouse [11]

I.3.2 Temperature

The temperature inside a greenhouse is one of the most important elements of the climate as it affects plant growth and development. The primary source of heat in an unheated greenhouse during the day is solar radiation, some of which is stored in the soil. The energy is primarily derived from the soil at night in the form of far IR radiation.

The shape and orientation of the greenhouse affect the solar radiation it receives at a given time and location, which in turn affects how hot the air inside is. The majority of the direct solar radiation is received at the floor of the greenhouse, which raises the temperature inside. Furthermore, the roof and each wall of the greenhouse accept diffusive and ground-reflected radiation, which means that the greenhouse's shape and orientation have a significant impact on the air temperature inside. [9]

Air temperatures in greenhouses are typically higher during the day and lower at night, regardless of climate. The interior air of the greenhouse and its various components interact with one another to exchange heat and mass, which results in temperature variations. [11] Numerous elements, including the amount of sunlight that enters the greenhouse, the ventilation system, the kind of insulation used, and the heating or cooling system used, can affect the air temperature inside a greenhouse.

During the day, due to the "heat trap" effect and a decrease in convective exchanges (as the air is confined), indoor air temperatures are higher than outdoor ones. [11]

The air temperature within the plant community and the temperature of the root zone have a substantial impact on plant development and flowering, consequently affecting crop yields [12].

In general, most plants grow best in soil that is between 65°F and 75°F (18°C and 24°C) in temperature. But different plants might have particular temperature preferences, so it's important to learn about the particular requirements of the plants being grown.

Heat stress is always impacted by the climate as a whole, water availability, $\mathrm{CO_2}$ and nutrient concentrations in the air and water, and other environmental factors. By this standard, an optimal growth temperature has a fluctuating terminus. The most expensive and energy-intensive intervention, cooling comes out ahead of all the other fixes. Therefore, before taking into account the technical measures of space cooling, it is necessary to consider the provision of a level for good growth at high temperatures in all stages of growth. [13]

I.3.3 $\mathrm{CO_2}$ Enrichment

When other growth factors, such as the availability of water, nutrients, and especially sunlight exposure, are met, $\mathrm{CO_2}$ enrichment in the greenhouse is an important parameter because it positively affects crop growth. Crop growth rates can be accelerated and production quality can be improved with better control of the necessary $\mathrm{CO_2}$ concentration. In order to make up for the significant reduction in $\mathrm{CO_2}$ caused by photosynthesis, $\mathrm{CO_2}$ amounts should be supplied to greenhouse crops, especially when adequate ventilation is lacking. [13]

Two main factors affect production losses in greenhouses [14]:

- Adequate ventilation to prevent $\mathrm{CO_2}$ depletion.
- Heating on sunny, chilly days to maintain a higher temperature despite $\mathrm{CO_2}$ exhaustion.

The amount of carbon dioxide ($\mathrm{CO_2}$) that has accumulated throughout the day is another significant factor that influences plant growth in a greenhouse. It is a crucial input parameter in the photosynthesis process and has a sizable impact on the productivity of greenhouse crops [15]. The range of 700.0-900.0 ppm is the optimal $\mathrm{CO_2}$ concentration for greenhouse crop production [16, 17]. When the $\mathrm{CO_2}$ concentration is below the ideal range, $\mathrm{CO_2}$ enrichment can be accomplished using a standard procedure for maximizing output and water use efficiency [18]. A regular increase in $\mathrm{CO_2}$ concentration inside the greenhouse could result in an increase in fruit yield of more than 20.0% for both fresh and dry matter. [12, 19]

For $\mathrm{CO_2}$ enrichment or heating, it is necessary to evaluate the installation and operating costs to determine the best climate control method. Increased ventilation or even $\mathrm{CO_2}$ enrichment appears to be a more cost-effective way to compensate for $\mathrm{CO_2}$ depletion than heating does compensate for production loss. Controlling $\mathrm{CO_2}$ concentration inside the greenhouse up to the outside level when ventilation is being used, and to higher levels when no or little ventilation is required for temperature control, can be done as part of a good management strategy. [14]

I.3.4 The humidity effects

The relative humidity (RH) of the air is an indication of how much water vapor is in the air at a particular temperature compared with how much water vapor the air could hold at that temperature. It is expressed as a percentage and can be defined as follows:

$$\mathrm{RH} = \frac{\text{amount of water in a given amount of air}}{\text{max. amount of water the air can hold at that temperature}} \times \frac{100}{1}$$

At 100% relative humidity, the air is said to be saturated because it can hold as much water as is physically possible at that particular temperature. At 10 °C, saturated air holds about 10 $\mathrm{g/m^3}$ of moisture; at 20 °C, about 17$\mathrm{g/m^3}$; and at 30 °C, more than 30 $\mathrm{g/m^3}$. Simply put, relative humidity is a measurement of the air's percentage saturation. Because of this, air at 50% relative humidity can hold 50% of its maximum amount of water, regardless of temperature.

The greenhouse's air is made more humid by soil evaporation and plant transpiration. These variables affect crop growth (transpiration rate, latent heat) and health in a variety of ways. Plants may be exposed to high RH levels, which can lead to environments that are particularly favorable to the growth of bacterial and fungal infections. However, if plants have a well-developed root system, air moisture in most greenhouses typically ranges from 40 to 100 percent. Normal plant development occurs at relative humidity levels of 20 to 80 percent. [20]

In addition, plants may experience water stress due to a decrease in relative air humidity brought on by an increase in air temperature. RH has an impact on pollen germination, pollen migration, and fruit size. Nonetheless, compared to open fields, a greenhouse offers a much wider range of options for humidity control. Aeration or ventilation is necessary to lower the humidity levels. [1] There are numerous ways to measure relative humidity, including acoustic sensors, polymer capacitive sensors, and semiconductor sensors. The measurement of relative humidity, however, is influenced by several environmental and practical factors. Reliability, long-term stability, accuracy, and precision measurements of relative humidity continue to be challenging in practice. Accurately measuring the inside and outside humidity levels in greenhouse climates can be difficult because the sensors are exposed to factors like changing solar radiation, shifting air movement, and direct water from rain, irrigation, or evaporative cooling equipment. [21]

I.4 Greenhouse geometry and dimensions

The design and dimensions of a greenhouse are primarily determined by the type and quantity of crops being grown, as well as the chosen climate control method. Greenhouses are constructed to create optimal environmental conditions for plant growth. It is important to minimize the impact of external factors such as wind, rain, snow, and crop load [22]. The orientation and shape of the greenhouse play a significant role in solar radiation transmission and sun elevation [23, 24], which in turn greatly influence the air temperature inside the greenhouse. It is crucial to adhere to technical requirements and minimum standards in greenhouse construction and operation.

I.4.1 Greenhouse shapes

The shape of the greenhouse plays a vital role in crop cultivation and production. Otherwise, the design of the roof determines how much solar radiation the greenhouse receives. [25] In hot and dry climates, the ideal greenhouse form should get the least sun irradiation during the summer and the most during the winter.

Greenhouses come in various shapes and sizes to cater to the diverse climatic zones found worldwide. Each zone necessitates different greenhouse designs to create favorable conditions for plant growth. Several factors guide the development of different greenhouse types, including maximizing insulation, covering a large ground area at a reasonable cost, and ensuring structural integrity. These criteria serve as guidelines in the creation of various greenhouse structures to meet the specific needs of different climates and facilitate optimal plant cultivation [26]. Some typical greenhouse shapes are shown in Figure I-2. [20, 27]

Crop production and cultivation depend heavily on the greenhouse's shape. Otherwise, the design of the roof determines how much solar radiation the greenhouse receives. [25] A greenhouse's most common structural design features a gable roof and straight sidewalls. A single span, twin spans, or a sizable greenhouse complex with gutter connections can all be built using any of these designs. In hot and dry climates, the ideal greenhouse form should get the least sun irradiation during the summer and the most during the winter. Crops in the tropics should be shielded from excessive global radiation, wind, and rain. The ratio of greenhouse volume to ground floor area should be as high as possible. At least 3m should be in the gutter height. [28]

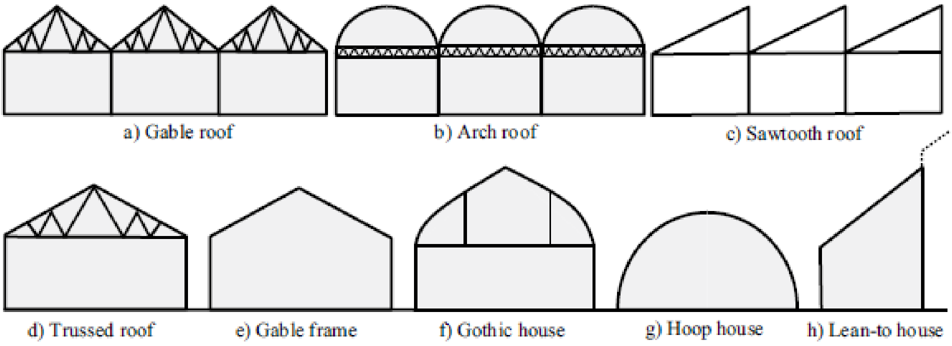


Figure I-2 Common greenhouse shapes [1, 20]

I.4.2 Frame and Cladding materials

I.4.2.1 Greenhouse Frame Materials

The materials most often used to construct greenhouse frames, either separately or in combination, are aluminum, reinforced concrete, steel, and wood. Just low walls and foundations are made of reinforced concrete. The majority of structural members are made of aluminum or galvanized steel. Aluminum is a popular choice due to its lightweight, corrosion-resistant, and low-maintenance properties. Steel is a strong and durable material but is heavier and more prone to rust and corrosion than aluminum. Wood is a natural and traditional option that provides good insulation but requires regular maintenance to avoid rot or warping. PVC is an affordable and lightweight material but may not be as strong as other options. The choice of frame material will depend on factors such as greenhouse size, environmental conditions, budget, and personal preferences. It is crucial to choose a material that can provide adequate strength and support for the greenhouse covering material while withstanding harsh weather conditions.

I.4.2.2 Greenhouse Cladding Materials

Greenhouse-cladding materials play a crucial role in creating a controlled environment for plants to grow. Cladding materials, also referred to as glazing, perform a dual function by blocking far-infrared radiation and allowing solar radiation required for plant growth. The amount and spectral distribution of solar radiation that eventually reaches the plant canopy are influenced by the radiative properties of the various cladding materials, which directly affect plant growth. [26] Furthermore, a greenhouse's moisture and carbon dioxide levels are indirectly impacted by the type of cladding material used.

The most common materials are:

- **Polyethylene film:** Polyethylene film is a cost-effective option for greenhouse cladding. It is lightweight and flexible, making it easy to install. However, it has a shorter lifespan compared to other materials and requires periodic replacement.
- **Polycarbonate:** Polycarbonate are renowned for their lightweight nature, durability, and excel-lent light transmission properties. They are particularly valued for their high impact resistance, making them a popular choice in regions with harsher climates, where they can withstand greater stress and provide long-lasting performance. Polycarbonate is also impact-resistant and provides protection against UV radiation.
- **Glass:** Glass is a traditional and popular choice for greenhouse cladding [26]. It provides good light transmission, allowing solar radiation to pass through easily. Glass also has excellent durability and is resistant to scratches and degradation over time. However, glass is heavy, expensive, and relatively fragile compared to other options [9].

- **Acrylic panels** are often considered an optimal choice for greenhouse applications due to their strength, lightweight, resistance to sunlight, and favorable light-transmission characteristics. While acrylic panels are susceptible to scratching, their main drawback lies in their relatively high cost. Nevertheless, the investment in acrylic is justified as it offers long-term reliability and durability, ensuring many years of satisfactory performance. [26]
- **Fiberglass Reinforced Panels (FRPs)** are rigid plastic panels manufactured from materials such as acrylic or polycarbonate. They are available in large sheets, either corrugated or flat. FRPs possess notable characteristics including durability, superior heat retention compared to glass, and lightweight construction. The key advantage of fiberglass lies in its exceptional resistance to breakage, ensuring a lifespan of approximately 10 to 15 years. These panels are particularly advantageous in areas with high light intensity, making them an appealing choice for greenhouse applications. [26]

These materials vary in terms of their durability, light transmission, insulation properties, and cost, and the choice of cladding material depends on factors such as the climate, budget, the level of maintenance needed, and specific requirements of the greenhouse. There is no perfect greenhouse cover; each has advantages and disadvantages and affects plant microclimates in different ways.

Glass and rigid plastic coverings are prevalent in colder regions like central and northern Europe, while plastic films are the primary cover materials used in warmer regions such as the Mediterranean area. [29]

Low thermal conductivity, high transmissivity to short-wave solar radiation, and low transmissivity to long-wave radiation are all crucial characteristics of greenhouse coverings used in winter greenhouses to conserve energy. In Table I-1, the significant thermal characteristics of popular greenhouse cladding materials are displayed. [20]

Table I-1 the shortwave (solar) and longwave (thermal) transmissivities of cladding materials are different [20].

Cladding material		Shortwave Transmittance (%)	Longwave Transmittance (%)	Estimated Lifetime (Years)
Glass	Single (double strength)	88	3	25+
	Insulated	75-80	<3	25+
	Solatex	91-94	<3	25+
polycarbonate	Single Wale Dynaglass	91-94	<3	10–15
	Macrolux Corrugated	91-94	<3	10–15
	Double Wall Macrolux	83	<23	10–15
	PolyCal	83	23	10–15
	Lexan Dripgard	83	23	10–15
Fiberglass	Lascolite	90	<3	10–15
Acrylic	Single Wall Plexiglass	93	<5	20+
	Lucite	93	<5	20+
	Acrylite	93	<5	20+
	Acrylic SPD	83	<5	20+
Polyethylene Film	Tufflite	<85	50	3+
	Standard UV	<85	50	3+
	Fog Block	<85	50	3+
	Sun Saver	<85	50	3+

I.4.3 Site Selection

Before a greenhouse complex is designed and built, choosing a good greenhouse site is the most crucial factor to take into account because it affects many essential requirements of a greenhouse operation. Consistent energy and water supplies are two of these necessities. The crop, planning, available plot size, and geographic location all play a role in choosing the greenhouse orientation that will produce the best results. A greenhouse complex should be situated so that it has easy access to markets for both the purchase and sale of its produce. The proposed greenhouse location needs to have sufficient communication tools, like a phone and fax machine. Electricity and water of a high enough standard should be readily available. [26]

For ease of personnel and material movement and to enable maximum automation, the service building and greenhouses should be on the same level. To lower the cost of grading, the building site should be as level as possible. The area should have good drainage. It is always wise to install a drainage system because greenhouse operations use a lot of water. Additionally, it is wise to pick a location with a natural windbreak on the north and northwest sides, such as a tree line or hill. Trees should be 100 feet (30.5 m) from greenhouses in areas where snowfall is predicted in order to prevent snowdrifts from encroaching on them. Trees located on the East, South, or West sides should be set back 2.5 times their height from the crop to prevent overshadowing. To make the system economically viable, the site must allow for facility expansion in the future. [26]

I.4.4 Greenhouse Orientation

When considering the orientation of a greenhouse, two key criteria are commonly taken into account [26]:

- Firstly, ensuring that the light level within the greenhouse is sufficient and evenly distributed to support optimal crop growth is essential.
- Secondly, it is important to position the greenhouse in a way that prevailing winds do not negatively impact the structure or the functioning of the facility.

The orientation affects the greenhouse's overall thermal performance because it can reduce the amount of solar radiation it receives. A cost-effective opportunity to increase greenhouse energy and thermal comfort is to choose the right orientation. The crop, planning, available plot size, and geographic location all play a role in choosing the greenhouse orientation that will produce the best results. [3]

For single greenhouses located above 40°N latitude in the northern hemisphere, it is recommended to construct them with the ridge running from East to West. This orientation allows the low-angle light of the winter sun to enter along the sides, rather than being blocked by the frame trusses at the ends. However, below 40°N latitude, single greenhouses should have their ridges oriented from north to south. This is because the angle of the sun is higher in these regions. [26]

In the case of gutter-connected greenhouses or multi-span structures, regardless of latitude, it is advisable to orient them in a north-south direction. This arrangement helps to avoid shadows that would occur if the greenhouse was placed immediately south of one another in an east-west orientation. While the north-south orientation may result in some shadow from the frame trusses, it is significantly smaller compared to the shadow cast by an entire greenhouse oriented to the south. [26]

The orientation of a greenhouse is also influenced by the prevailing wind direction at the site. In the case of naturally ventilated greenhouses, it is advisable to position the ventilation openings on the side facing the direction of the prevailing wind. To mitigate the impact of wind, fences of different heights or the strategic planting of trees and shrubs can be implemented as windbreaks. It is important to note that a solid windbreak, which creates turbulence, is less effective compared to one that allows a controlled amount of wind to pass through it. Therefore, the design of windbreaks should consider this factor for optimal greenhouse performance. [26]

On the other hand, the shading brought on by the nearby terrain, buildings, and plant material has a significant impact on a greenhouse facility. As a result, greenhouses shouldn't be built close to big trees, big buildings, or other obstructions. According to general guidelines, nothing taller than 3.3 m shouldn't be located within 9 m of the greenhouse in either an east, west or south direction. The size of the shadows is influenced by the angle of the sun and, consequently, by the time of year. [26]

I.5 Conclusion

The design of greenhouses is crucial in semi-arid regions to mitigate the challenges of water scarcity and extreme climatic conditions, promoting sustainable agriculture and enhancing food production. The choice of greenhouse shape is important, with optimal shapes such as curved or sloping roofs promoting efficient rainwater collection, better air circulation, and temperature regulation. The selection of appropriate cover materials is critical, with high light transmission and insulation properties, and UV-blocking capabilities protecting plants from radiation. Orientation is also crucial in maximizing energy efficiency and optimizing resource utilization. Through thoughtful consideration of these factors, greenhouses can combat the challenges posed by water scarcity and extreme climate conditions, fostering sustainable agriculture and food security in these vulnerable areas.

In the next chapter, we will delve into an in-depth discussion of the various systems that have been implemented for managing indoor greenhouse climates.

CHPTER II: Literature review

II.1 Introduction:

The big problem that has been bothering scientists in recent years is population inflation and how to provide food for all people on the surface of the globe, which made things worse by climate change and its impact on agricultural crops and their quality. For this reason, the greenhouse was invented in order to provide the appropriate climate for the plant (light, heat, CO2, humidity, etc.). But scientists faced several problems with heating and cooling costs, which made them turn to renewable energy and passive cooling and heating methods in order to reduce heating costs. This chapter will cover a review of the literature in the field of agriculture in greenhouses, especially those dealing with the issues of greenhouse conditioning by various heating and cooling methods in recent years, especially those concerned with the economic aspect and cost reduction as much as possible.

I.2 Greenhouse heating technologies

The three most common types of air heating systems (Figure II-1) are: (1) fan coils; (2) hot air generators; and (3) heat pumps (water/air or air/air).

Fan coils transfer heat from hot water flowing through metal pipes to the air, with water fan coils being the most common type.

Hot air generators, use fuel to heat the air, which is pushed into the greenhouse and circulated. They have the option of using direct or indirect combustion.

Heat pumps, are also used for air heating in greenhouses. In a water/air heat pump, heat is transferred from water to the air, while in an air/air heat pump, heat is extracted from the ambient air and transferred directly to the greenhouse air.

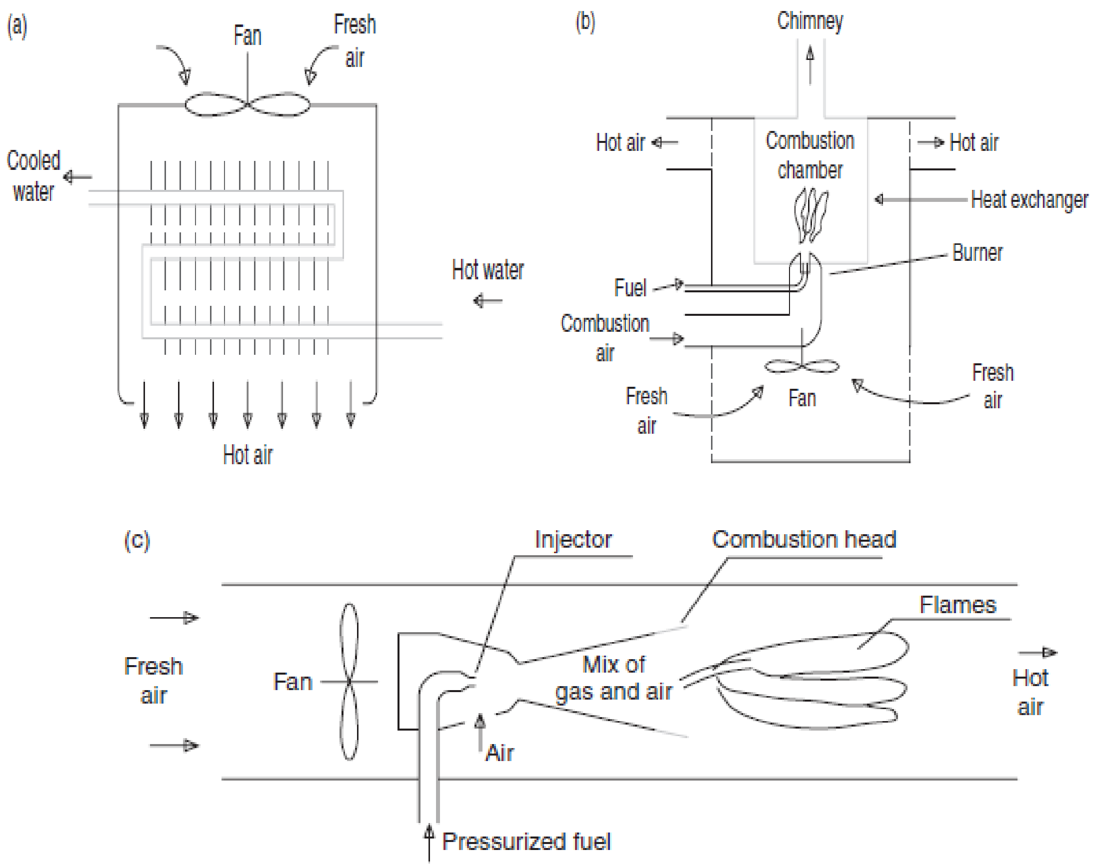


Figure II-1: Air heating systems: fan coil (a); hot air generator using indirect combustion (b) and direct combustion (c). [11]

Passive solar greenhouses are outfitted with heat collection systems that are integrated into the greenhouse's cell or the greenhouse itself is used as a collector because it is designed to maximize solar gains. Some applications do not include a heat storage system. In this case, several passive solar techniques are used to meet the greenhouse's heating requirements. Some greenhouses, for example, use the geometry of the cell to maximize solar gains. Other greenhouses use reflective surfaces on the north side and insulate the north, east, and west sides to trap incident solar radiation inside the greenhouse during the winter months. [30] For example, increasing the span expand the soil and south roof areas, giving you more space to plant crops, but it also changes the thermal environment inside the greenhouse. As a result, various studies have been conducted to determine how the span affects interior temperatures, with higher temperatures for longer periods of time during the winter resulting in better crop production. [31] The greenhouse's shape is critical in crop cultivation and production. Otherwise, the shape of the roof determines the amount of solar energy received by the greenhouse. [1]

There are five categories of passive solar greenhouses according to the characteristics of the heat storage medium, namely:

- Water storage,
- Latent heat storage,
- Rock bed storage,
- Soil storage with buried pipes
- Other types of heat storage [30].

Figure II-2: Thermal heat storage mediums inside PSGs; a) PCM pipes ("Fashioning a Greenhouse: Hobby Greenhouse with PCM Pipes," n.d.), b) Water barrels ("Tips on Using Water Barrels in a Solar Greenhouse | Cere Greenhouse," n.d.), c) Rock bed ("Solar greenhouse - Ecodiy DIY eco-house," n.d.). [30]

Bargacha et al., (Morocco 1999) used the FPC system shown in the figure .The hemi cylindrical experimental greenhouse is covered with a thermal polyethylene film. It has a 25°W orientation and dimensions of 10 m width, 25 m length, and 3.40 m height. The greenhouse is ventilated by opening the plastic bands on the lengthwise sides and the width wise ones. The experimental greenhouse is next to the reference greenhouse, which has the same cultivation. The heating system consists of the elements shown in the Tableau II-1 and detailed drawing of it at Figure II-3.

Tableau II-1: The heating system consists.

Fat plate collectors	Optical surface of 2.34 m^2
Two tanks (cold water/worm water)	250 L for one of them
An agrotherme type heat interchange tube	25mm
Greenhouse	10m * 25m * 3.4 m

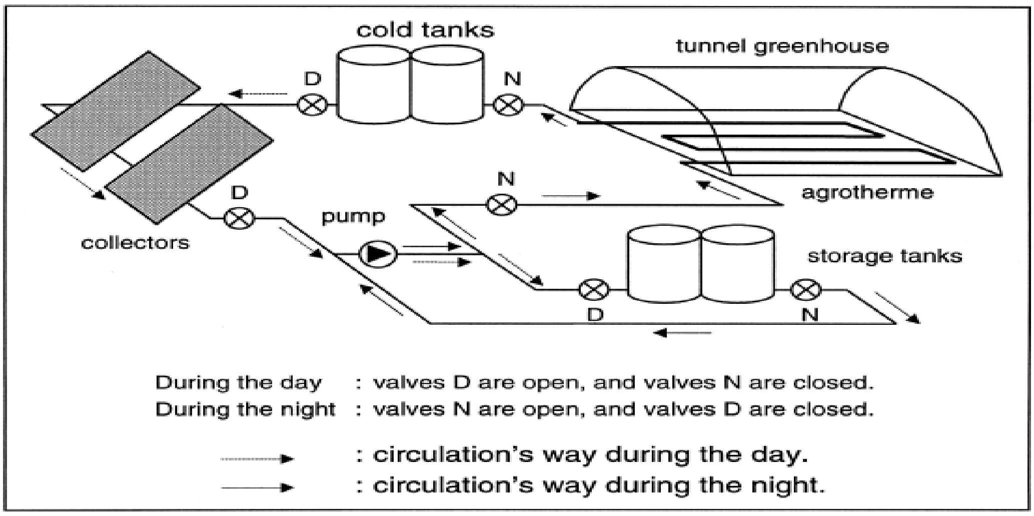


Figure II-3: Schematic of the greenhouse heating system using solar flat plate collectors.[32]

Where you get the following results:

- Increasing the temperature inside the greenhouse by 1.2 degrees.
- Appropriate distribution of heat inside the greenhouse.
- The maximum speed of watermelon harvest is 14 days [32].

Xu et al., (China2020) installed solar collectors to heat water vertically on the northern wall, in addition to an underground tank for storing warm water and using it at night. The experimental results showed an average daily heat collection rate equal to 72.1% [33]. In Turkey in 2005 H. O¨ ztu¨rk worked on this system: The major components of the heating system are FPCs (1.5 m2), an LTES system (6000 kg of paraffin), and a heat transmission unit. According to the findings, the suggested system's average net energy efficiency is 40.4%, while its energy efficiency is 4.2%. [34]

Lazaar et al., are constructing and installing two tunnel greenhouses with a total surface area of 100 m² at the CRTEn (Research and Technology Centre of Energy) in Tunisia. The first has a subsurface and suspended heat exchanger, whereas the second does not have a heating system. To raise the nightly air temperature in the greenhouse, two heating systems were used: an Electrical Heating System (EHS) and a Solar Heating System (SHS). Compare the two heating methods through research. The solar collector's efficiency is determined, and the usefulness of the evacuated tube solar collector with a water storage tank is also investigated. The evacuated tube solar water heater has an average energy efficiency of 46%. [35]

Hassanien et al., (China 2018) employed an evacuated tube solar collector as a solar water heater supported an electric heat pump for greenhouse heating an electric heat pump for greenhouse heating. The solar collector's thermal efficiency and payback period were 0.49 and 4.1 years, respectively. This integration can offer more than 35% of a greenhouse's total heat need. [36]

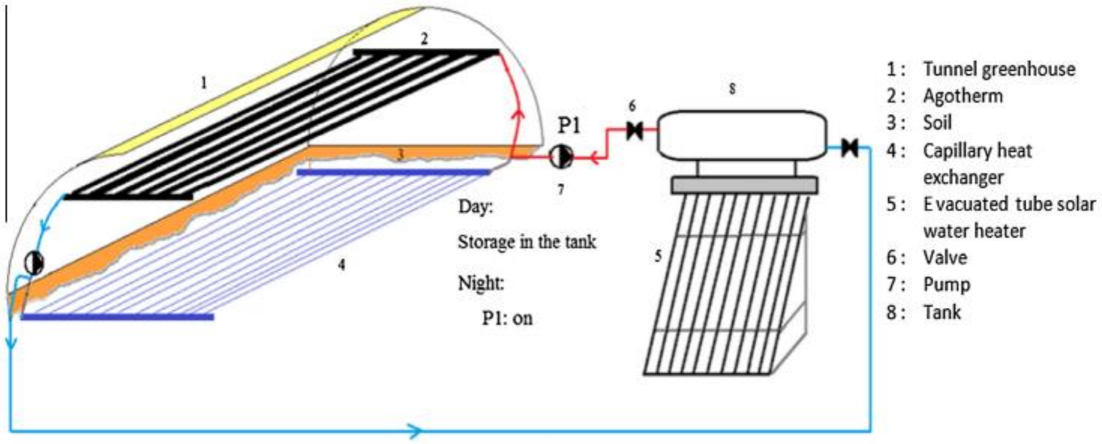


Figure II-4: Greenhouse heating by an Electrical Heating System (EHS). [35]

Researchers have rarely investigated the integration of solar concentrators with greenhouses, so more research is needed, particularly in terms of controlling the temperature provided by concentrators. Integrating concentrators with greenhouses necessitates the installation of sun-tracking systems, which raises the overall cost of the system. Because they can transmit the majority of incident light into the greenhouse, Fresnel lenses are the best concentrators for integration with greenhouses. [37]

Imtiaz Hussain and colleagues compare the thermal performance characteristics of LFL and SFL solar collectors (linear and spot Fresnel lens, respectively) heating similar greenhouses in Chuncheon, South Korea (2015). The results showed that the SFL collector had higher available power per unit area and thermal efficiency than the solar collector LFL. When the storage capacity of either pool was increased, the discounted payback period decreased and the electricity savings increased. All results showed that the performance of the SFL collector was 7-12% higher than that of the LFL collector. [38]

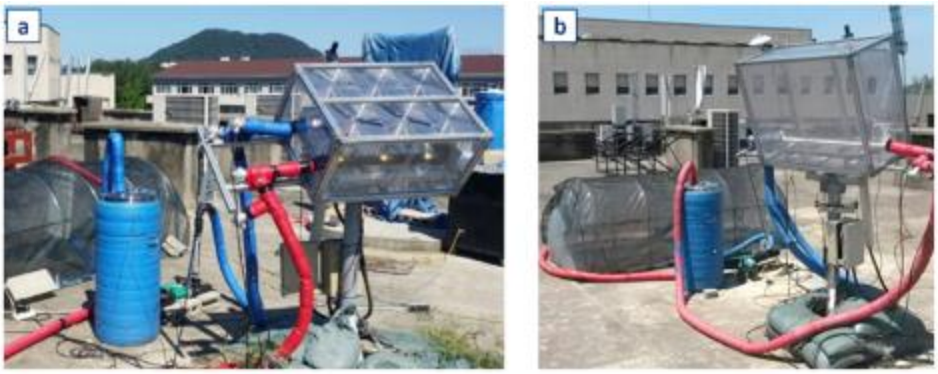


Figure II-5: Experimental setup: a) SFL collector system b) LFL collector system. [38]

Ku¨rklu et al. (2003) A study was carried out to investigate the storage of solar energy in an underground rock bed for greenhouse heating. Tests were conducted in two identical polyethylene tunnel greenhouses with 15 m^2 ground area each. Two excavated and insulated channels were filled with rocks. One of the greenhouses' soils. A centrifugal fan with an 1100 m^3/h air flow rate drove greenhouse air through the rock-bed and was controlled by two thermostats when energy storage or release was required. There were no crops produced in the greenhouses, and the vents were kept closed unless there was severe humidity inside the greenhouses. According to the findings of this investigation, the rock-bed system caused an air temperature difference of around 10 °C. Figure II-6 shows the details of the experiment. [39]

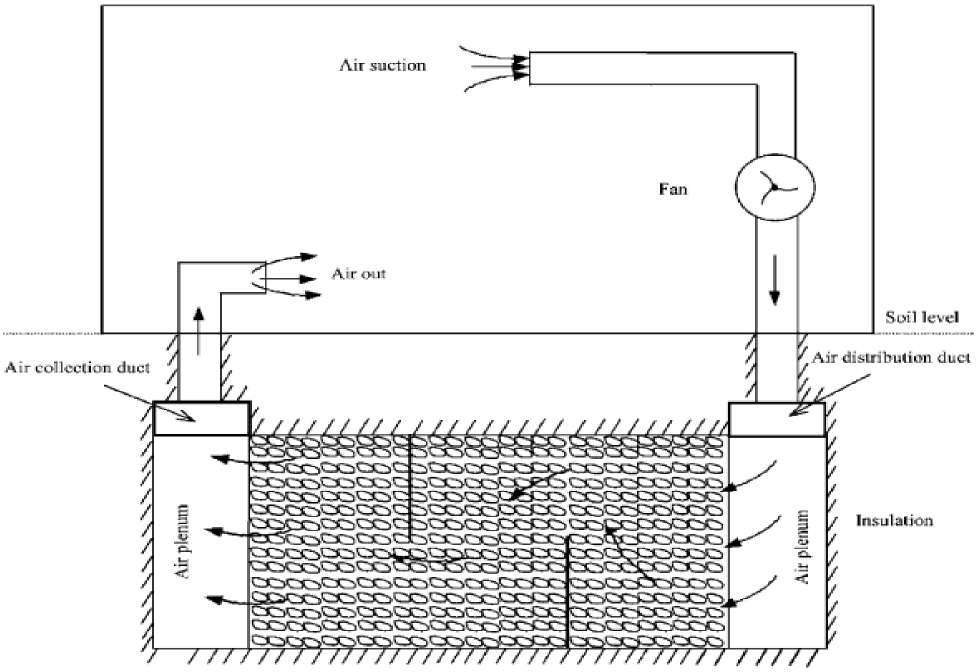
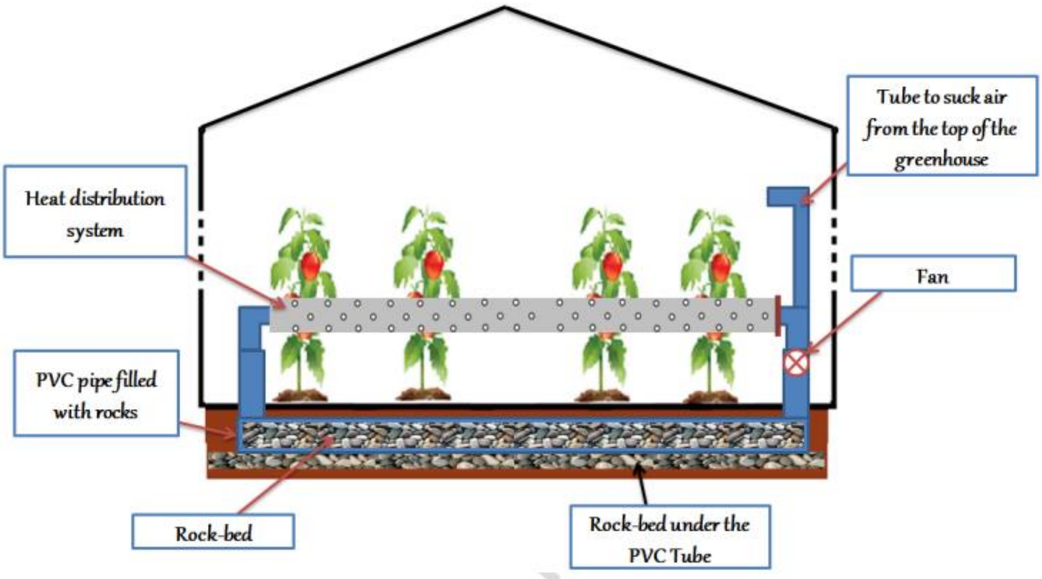


Figure II-6: Front-cut views schematic of the experimental set-up. [39]

Gourdo et al., (2019) conducted a study focusing on the utilization of a rock energy storage base for heating the ambient air inside a canary-type greenhouse. The objective of the system was to store excess heat during the day and release it at night, thereby regulating the greenhouse temperature. The experimental measurements of climatic parameters provided valuable insights into the performance of this setup. The experiment presented in Figure II-7 demonstrated that the use of the rock energy storage base led to a notable increase in the air temperature within the equipped greenhouse. During the night, a temperature drops of approximately 3 °C was observed, while during the day, the temperature decreased by 1.9 °C. This indicates that the system successfully provided heating during the day and cooling during the night, contributing to a more controlled and optimal growing environment. Moreover, the implementation of the rock energy storage base had a positive impact on crop yield. The study reported a significant 22 percent increase in tomato yield as a result of employing this system**.**[40]



FigureII-7: Schematic of the heating system with rock-bed installed in the greenhouse. [40]

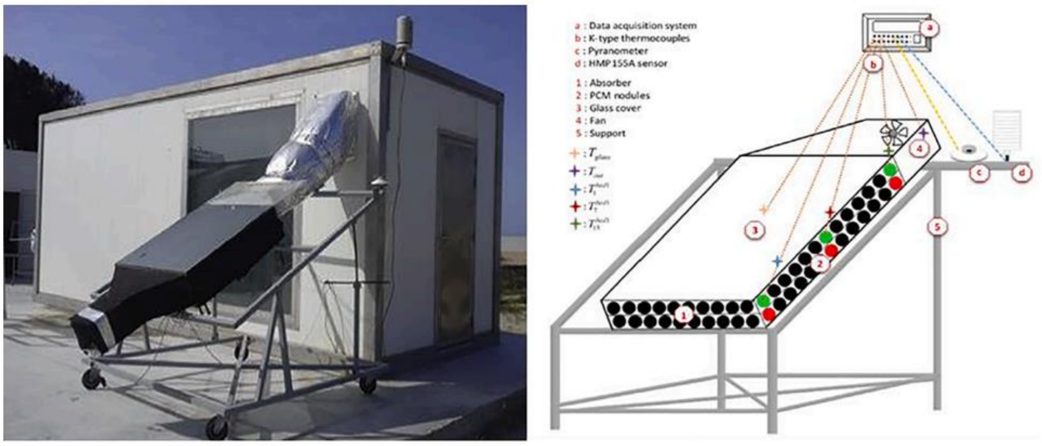
Semple and al., (2017) study combined a large-scale solar collector system with seasonally stored thermal energy. The TRNSYS program was used to create low- and high-temperature thermal energy storage systems, and their performance was compared. With many positive attributes, systems capable of covering up to 65% of the annual greenhouse heating demand are discussed. The systems can reduce carbon dioxide equivalent emissions by about 220 tons per acre.

Mavrogianopoulos and Kyritsis., (1993) tested a greenhouse integrated with a passive solar system that collected and stored heat using water. In their case, Water was stored in transparent polyethylene tubes located between the rows of cultivated tomato plants on the greenhouse soil. During January, the minimum inside air temperature was 3 et 4 °C higher than the outside, with a solar energy collection factor of 90%. [41] Also in a previous study**. Bargach et al., (1999)** developed a heating system to improve the microclimate inside a greenhouse using solar FPCs.

The PCM is used in this type of system (LTES), as it offers a higher energy density than STES. The melting temperature of selected PCMs should range from 20 to 60°C which makes them suitable for use in greenhouses. PCM materials are also divided into organic and inorganic materials. Paraffin, for example, is the most common material in this field, with a rate of 30 % of the total applications. [42] So that the choice is made between different types through their different properties, such as melting point, freezing point, price...etc. Two identical greenhouses were used in this study. One uses a latent heat system for heating, which was built and installed at CRTEn (Centre for Research and Energy Technology) in Tunisia. This heating system consists of a new solar air heater collector consisting of a packed bed of spherical capsules filled with phase change materials. The solar air heater was installed inside a greenhouse filled with tomato plants and operated all winter long See Figure II-8. The heat recovered at night for this system met 30% of the total heating requirements. [43]

Figure II-8: a) External view of the insulated greenhouse, **b)** Solar air heater with LTES inside the greenhouse [43]

Baddadi et al., (2019) created a novel hydroponic greenhouse integrated into a solar air heater with PCM and studied its microclimate. The results showed that the developed greenhouse provided a better environment than conventional greenhouses. Furthermore, a 6 °C increase in the interior air temperature of the greenhouse with two packed beds of LTES was observed during the night [44]



(a) (b)

Figure II-9: (a) The solar air collector equipped greenhouse along with packed bed PCM and **(b)** schematic view of the packed bed solar thermal collector. [44]

A. Barbaresi et al., (2020) focused on evaluating the performance of a geothermal system in a case study farm. The research aimed to determine the optimal conditions for measuring thermal humidity, which is crucial for cultivating three different crops in protected areas. The geothermal system primarily operated at night, allowing for thermal recovery from the Earth during the day. [45].

Al-Hel et al. (2022) looked at the geothermal energy potential for cooling and heating greenhouses in hot, arid climates. The scientists found that the best depth for burying Earth-to-Air Heat Exchanger (EAHE) pipes was 3 meters. In the summer, the ground temperature at this depth was 32°C, while in the winter, it was 29°C. These temperatures allowed the greenhouse to emit moist air with a maximum cooling or heating capacity of 1000/890 MJ per day per cubic meter.[46]

II.3 Greenhouse cooling technologies

II.3.1 Natural Ventilation Cooling

The use of wind and buoyancy driven flows to provide cooling in greenhouses dates back to the early days of controlled environments. This simple technology requires little or no external energy and can be useful for greenhouse cooling applications in hot areas. It is caused by the pressure difference between the greenhouse interior and the outside environment (Figure II-10). This is accomplished by carefully arranging side wall and roof apertures.

Teitel, Montero, and Baeza (2012) studied a new five-span greenhouse design with a 30 slope roof, side wall vents, and roof vents for each span. Deflectors were installed on the ridges of the windward and leeward spans, as well as on the side wall vents, to prevent hot and dry wind from directly impinging on the plants. The proposed design was compared to a typical parral-type greenhouse with a shallow slope roof, small vertical and sidewall vents, and no deflectors. The results showed that the proposed design may provide up to four times the ventilation rate of the parral-type greenhouse. There was also an improvement in air circulation and temperature dispersion in the greenhouse. [47]

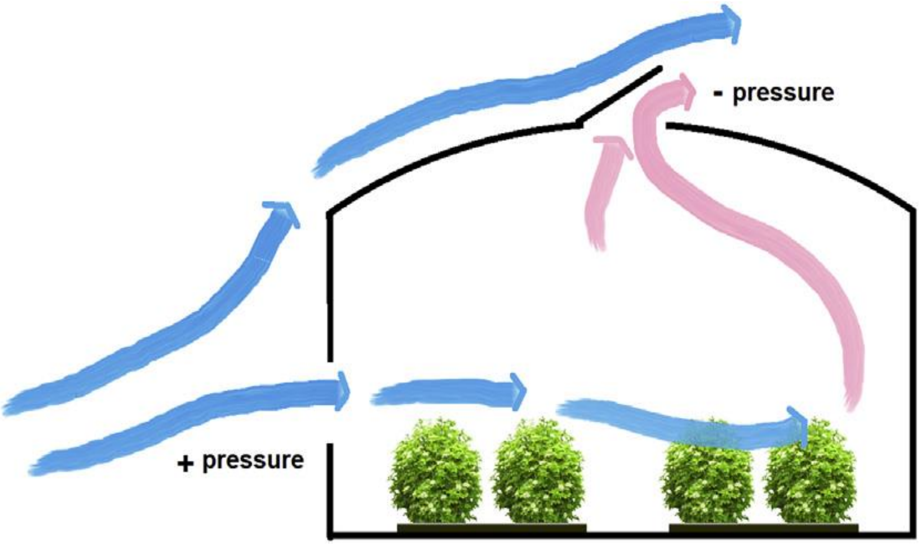


Figure II-10: Naturally ventilated greenhouse driven by pressure difference. [47]

II.3.2 Forced Ventilation Cooling

Forced ventilation is a method that can be utilized to reduce the temperature inside a greenhouse [11]. the optimal airspeed for forced ventilation should be approximately $0.5\ \mathrm{m}^3/S/\mathrm{m}^2$ (Willits, 2003). Helical fans are utilized to introduce or extract air from the greenhouse as depicted in Figure 2, enabling substantial airflow at low pressures. These fans are designed to operate at low rotational speeds due to their noise production and high electricity consumption [1].

Figure II-11: Forced ventilation cooling in a greenhouse **[1]**

II.3.3 Fan-Pad System

In horticulture, the fan and pad cooling system are most commonly used. Outside air is blown or sucked through large-surfaced pads. The pads are kept permanently wet by sprinkling water on the surface of the pad, which evaporates and cools the air (Figure II-12).

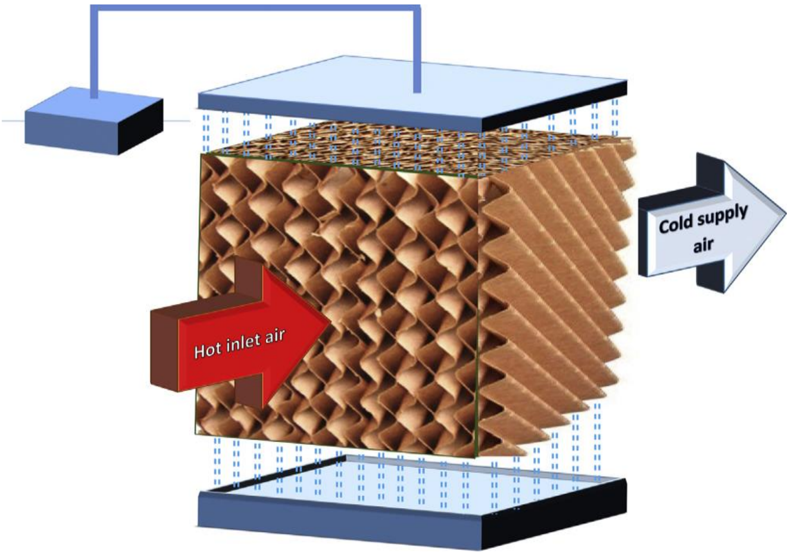


Figure II-12: Schematic of evaporative pad [48]

The greenhouse should be shaded for maximum cooling. There are two types of fan and pad cooling systems as shown in Figure III-13.

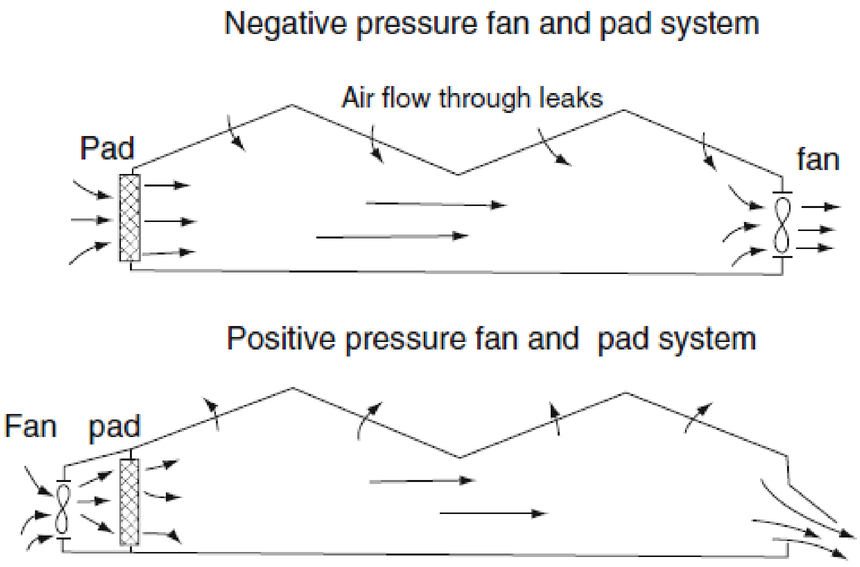


Figure II-13: Negative and positive fan and pad systems. [14]

Camara-Zapata et al., it was discovered that the implementation of evaporative pads in greenhouses has several effects. Firstly, it reduces the overall temperature within the greenhouse, while simultaneously increasing humidity levels. Additionally, it has a slight impact in reducing leaf temperature transpiration. However, it was observed that transpiration rates experience a significant drop. The study recommends the utilization of fan and pad evaporative cooling systems in hot and dry climates. On the other hand, in hot and humid climates, natural ventilation technologies are deemed more suitable. It is important to note that the study also highlighted a decrease in the cooling efficiency of the fan and pad cooling system under extreme climatic conditions. [45]

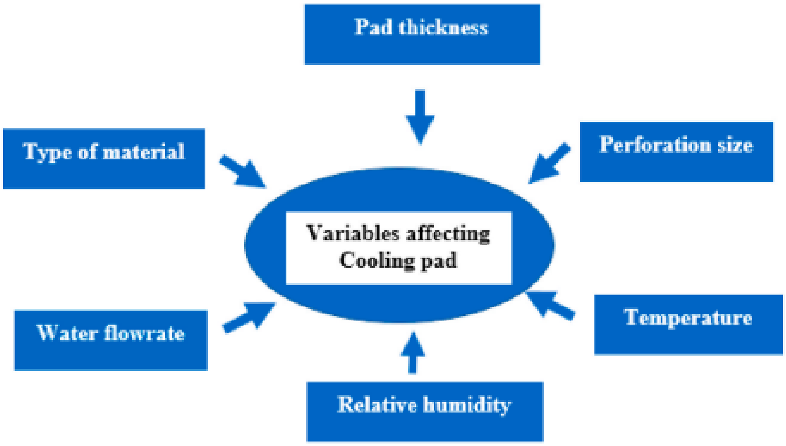


Figure II-14: Important variables affecting cooling pad performance.[49]

Reddy et al., [50] did not fully rely on the greenhouse's natural ventilation; instead, the authors used a fan and pad system. The fan and pad system were able to reduce the greenhouse temperature by up to 8 °C during the day, particularly at noon. The greenhouse temperature was kept at a constant 2 °C by using natural ventilation. Another study in an even-span greenhouse found that the Se'd (Nut-grass) pad had the highest cooling efficiency of 88.4%, compared to the Purdy and Samar pads, which had efficiencies of 83.1 and 79.6%, respectively [51]. A study (Figure II-15) A schematic view of a fan and pad evaporative cooling system in a greenhouse [52].

Chandra et al., [53] conducted an experimental study in a 24 m² plastic-covered greenhouse, focusing on the application of a negative pressure fan and pad system for cooling. The researchers employed Landsbergis model to predict the air temperature inside the greenhouse. As a result, a significant decrease in the internal air temperature, ranging from 4 to 5 °C, compared to the outside conditions was achieved. This demonstrates the effectiveness of the fan and pad system in providing cooling and creating a more favorable environment for plant growth. In a study by Jamal [54], evaporative cooling in a commercial greenhouse equipped with a fan and pad system was investigated, specifically during the summer period in arid countries. The researcher determined that a volume flow rate of 20 air exchanges per hour was necessary to maintain favorable conditions inside the greenhouse, particularly under dry weather conditions. This highlights the importance of adequate air circulation and ventilation to optimize the cooling efficiency and create a suitable microclimate for plant cultivation in arid regions.

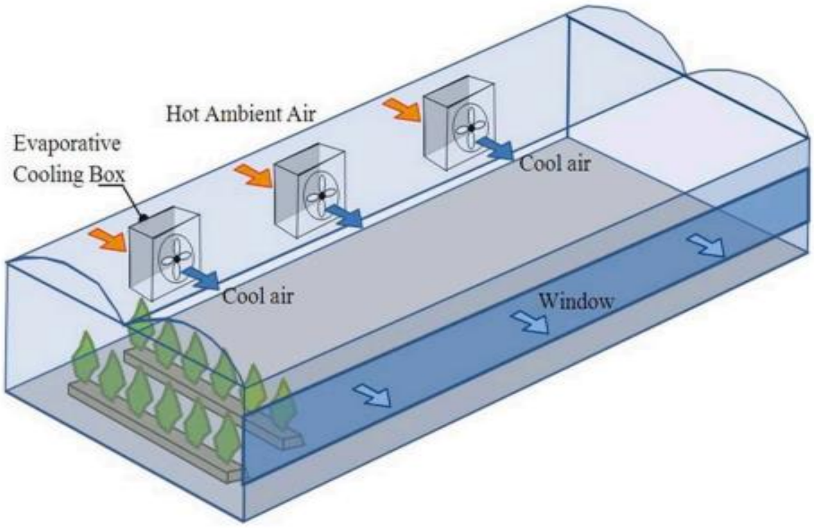


Figure II-15: A schematic view of a fan and pad evaporative cooling system in a greenhouse [52]

Gunham et al., (2007) conducted a literature review on different pad materials and their respective efficiencies (shown in parentheses). For instance, the study reported the efficiencies of wood shavings (69%), discarded clay brick, charcoal, coir fiber (89-90%), fine fabric (47-85%), and coarse fabric (64-86%). Additionally, Von Zabeltitz (1986a) provided efficiency values for wood excelsior (90-95%), coke (70-90%), and expanded clay (85-95%). [14]

Gunham et al., (2007) conducted a comparison study on different pad materials, including pumice stones, volcanic tuff, shading material, and corrugated cellulose. They observed that pumice stones and volcanic tuff achieved a pad efficiency ranging from 70% to 85% when using a water flow rate of 3.5 l/min per meter of pad length, air velocities of 0.5 to 1.5 m/s, and a pad thickness of 150 mm. On the other hand, the corrugated cellulose pad exhibited an efficiency of 75% to 80%. [14]

II.3.4 Fog/Mist System

This technology utilizes pressurized water sprayed through small nozzles to create a fine mist above the crops, providing cooling. The water droplets have a low terminal velocity, allowing the greenhouse air streams to carry them easily (Figure II-16). As a result, there is a high evaporation rate of water, effectively cooling the environment while keeping the crops dry. (Abdel-Ghany & Kozai, 2006). Numerous studies have been conducted to explore the efficacy of fog and mist cooling systems in greenhouses

Montero et al., [55] used an air water fogging system with a shade screen that had 45% perforations to cool a greenhouse. The study reported a maximum temperature reduction of 5 °C during sunny days. Similarly, Arbel et al. [56] investigated the effectiveness of a fog system utilizing droplets ranging in size from 2 to 60 µm in a greenhouse measuring 16 m × 24 m, specifically under the climatic conditions of Israel. The performance of the fog system was compared to that of a fan and pad system. The researchers concluded that the fog system exhibited superior performance compared to the fan-pad system, as it resulted in temperature and relative humidity variations of less than 5 °C and 20%, respectively.

Katsoulas, Baille, and Kittas (2001) conducted a study to examine the impact of misting on transpiration and conductance of rose canopies in a greenhouse. The experiments took place in the summer, and a mist system was activated when the relative humidity inside the greenhouse dropped below 75%. The results revealed that the mist system contributed up to 20% of the overall evaporative cooling, although only 40-50% of the mist water was effectively utilized for cooling purposes. However, the calculated crop water stress index indicated that the plants experienced reduced stress levels during misting conditions. [47]

Misra and Ghosh., (2017) created a simplified thermal model for a fog-cooled greenhouse with natural ventilation [51]. The model was validated using an experimental arched shape plastic greenhouse in eastern India. They discovered that the inside temperature of the greenhouse is solely determined by fogging configurations and discovered the best fogging cycle when the spray time to interval time was 1.5-2.0 min. (Figure II-18) depicts the schematic diagram. Finally, they concluded that with a low-pressure fogging system and adequate ventilation, the greenhouse's interior temperature could be kept 2o°C - 4o°C lower than the ambient temperature.

In a further study**, Katsoulas et al., (2006)** evaluated the effect of fog cooling on the microclimate and quality of a soilless pepper crop in a greenhouse in a subsequent investigation. The greenhouse was divided into two sections that were cooled by natural ventilation through roof openings that kept the air temperature below 26 °C and fog cooling through open roof vents to the maximum aperture to keep relative humidity below 80%. When compared to natural ventilation, fog cooling can reduce indoor air and leaf temperature by up to 3 °C. Furthermore, even during the hottest part of the day, the air vapour pressure deficit was less than 2 kPa under fog circumstances. The fog system was also said to have increased the average crop weight and the proportion of marketable crop. [47]

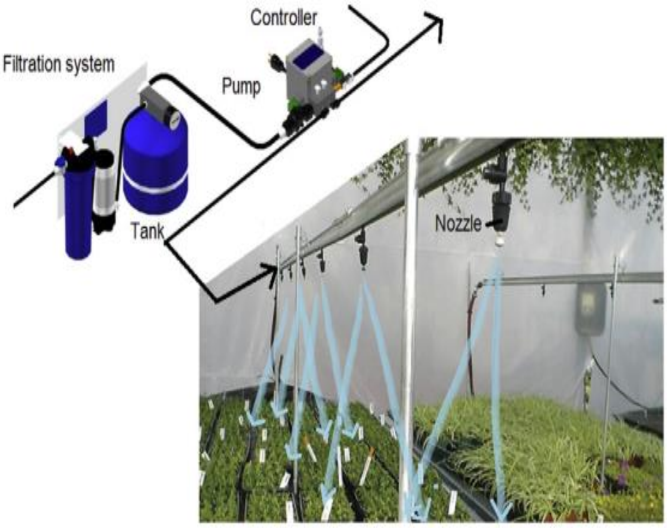


Figure II-16: Schematic of a greenhouse fogging or misting system installation. [47]

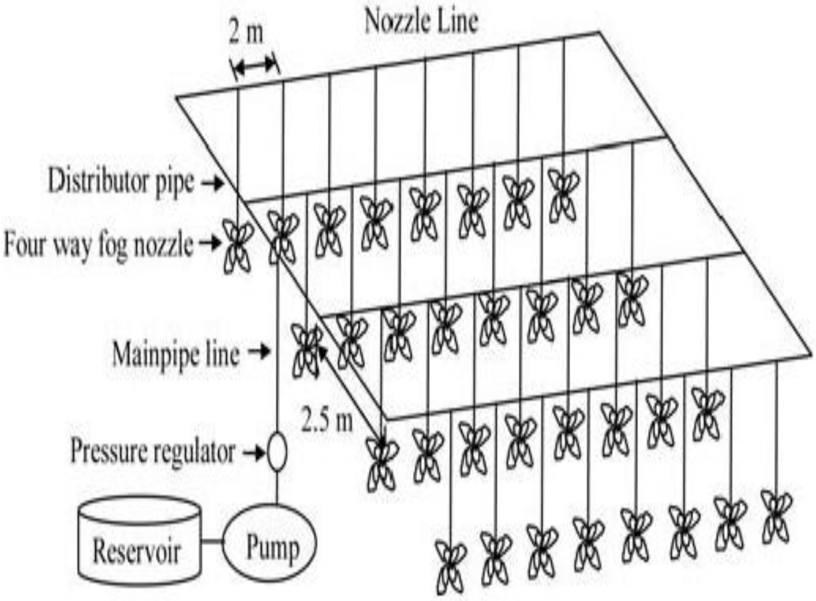


Figure II-18: Schematic diagram of fogging system components [51]

Figure II-16: Greenhouse water fogging. [11]

A study indicated that the pulse-width modulation strategy saves water consumption by up to 15 percent. In the same study, a comparison was made between the fogging system and the shading system with a fogging cooling, where the results concluded that they have the same effect as changing the temperature, except that the humidity is much lower. in the last system [57].

II.3.5 Shading

Shading is a widely employed technique by growers to mitigate the solar heat load in greenhouses. It involves reducing excessive solar radiation during summer periods and can also serve as insulation during winter, as indicated by studies conducted by **Willits (2001) and Chen et al. (2011)**. Various methods of shading have been utilized to lower the internal energy levels in greenhouses.

Al-Helal and Al-Musalam (2003), state that shading is typically done by filling acrylic channel-glazed greenhouses with polystyrene balls and utilizing porous materials like porous clothing and plastic nets, white lime sprayed on the exterior of the greenhouse glaze as depicted in Figure II-19, and porous materials such as these to shade the plants. Additionally, shade can be accomplished by filling two layers of a polyethylene glass greenhouse with retractable liquid foam. One can control foam density. [58]

Figure II-19: Whitewash applied on the outside surface of the glazing [1].

Growers have long utilized whitewash shading to reduce transmitted solar radiation and improve the microclimate in their greenhouses. The outside of glass and plastic greenhouse glaze is painted with a solution created by combining a certain amount of calcium oxide or calcium carbonate with water **(Baille et al., 2001; Chauhan et al., 2003)**. Whitewash shading, however, is erratic and susceptible to erosion during heavy downpours **(Ganguly and Ghosh, 2011)**. Additionally, this shade technique can lessen the needed optical capability for plant photosynthesis. [59]

Plastic nets are an effective method of shading to address thermal gradients and reduce thermal stresses in greenhouses, as noted by **Sethi and Sharma (2007)**. Numerous studies have demonstrated the benefits of using shading nets in improving greenhouse environments, enhancing cooling system performance, and increasing efficiency. Additionally, shading nets can contribute to reducing energy consumption in fan-pad cooling systems and minimizing irrigation water usage, as observed by **Al-Helal and Al-Musalam (2003)**. Shading nets vary in terms of color, texture structure, porosity, and shading factor, with lateral shading being a crucial factor affecting the amount of solar radiation transmitted into the greenhouse. [58]

Camilo et al., [60] conducted a study to assess the impact of reflective aluminized polypropylene shading nets on the photosynthetic performance of citrus plants. The researchers observed a reduction in photo-synthetically active radiation (PAR) levels and leaf temperatures when the reflective nets were used.

Ali et al., [61] developed an efficient greenhouse design specifically tailored for hot climatic conditions in Kuwait. In their study, solar radiation was allowed to enter the greenhouse only through the roof of the even span structure, which had a floor area of 250 m² and was used for tomato cultivation. A screen mesh with 55% shade was employed to shade the roof, and a fan-pad system was utilized during peak hours to regulate the internal air temperature. The results demonstrated that the combination of shading and the fan-pad system effectively maintained temperatures of around 30 °C during the day and 22 °C during the night inside the greenhouse.

II.4 Conclusion

In this chapter, various methods for heating and cooling agricultural greenhouses have been explored. Ventilation and shading systems are considered cost-effective options with significant cooling effectiveness. However, the fogging system is identified as the most efficient method. In terms of heating systems, solar collectors are recognized as one of the top choices, although research in this field remains limited. There is a need for further development and adaptation of these systems to align with farmers' perspectives and economic considerations. Therefore, it is advised that researchers approach this topic from multiple angles, giving importance to cost-effectiveness and the practicality from the farmers' point of view. By considering these factors, advancements in greenhouse heating and cooling systems can be achieved, promoting sustainable and farmer-friendly solutions.

Chapter III: Material and Methods

III.1 Introduction:

Effective temperature management is of utmost importance when it comes to maintaining specific environments and regulating both hot and cold conditions. In this chapter, we will present the different systems that have been specifically designed and tested for this purpose. These systems include the solar heating system, natural ventilation system, shading system, and evaporative cooling fan pad system. A detailed description of the experimental tools, fixtures, and equipment utilized in carrying out the experiments will be provided. Additionally, we will present the instrumented employed to collect data, ensuring accuracy and reliability in our findings. By thoroughly examining these systems and their associated experimental setup, we aim to shed light on their effectiveness in achieving temperature control objectives. This knowledge will serve as a foundation for the subsequent analysis and discussion of the obtained results in the following chapter.

III.2 Experimental Site

The study was conducted at the Experimental Platform for Applications of Renewable Energies in Agriculture (URAR), Ghardaia region, Algeria (32°28' N latitude, 3°40' E longitude). The Ghardaia region, located within the Sahara Desert, has a hot desert climate characterized by high temperatures and limited rainfall. Summers are extremely hot, exceeding 40 °C, while winters are relatively mild, with lows around 10 °C. Annual rainfall is low, averaging about 60 mm (2.4 inches), primarily falling during the winter season. Relative humidity is generally low in summer but can reach around 85% during rainy periods. The region experiences moderate to strong winds and abundant sunshine, making it suitable for solar energy research.

Figure III-1: Experimental platform for applications of renewable energies in agriculture

III.3 Experimental greenhouses

The experiments were carried out in two identical double-span experimental greenhouses. Each greenhouse has gross dimensions (length × width × height) of 2m × 1.6m × 0.65m, and a net floor surface area of 3.2m² as shown in Figure III-1, both two greenhouses were covered with a 200µm thick polyethylene thermal plastic film anti-drip-lock and UV-reflected (Table III-1), a white color. During experiments, natural ventilation, shading, irrigation and Fan-Pad systems were actively used to ensure proper climate for growing crop. Figure III-3 represents the external view of the two greenhouses experimented in this study.

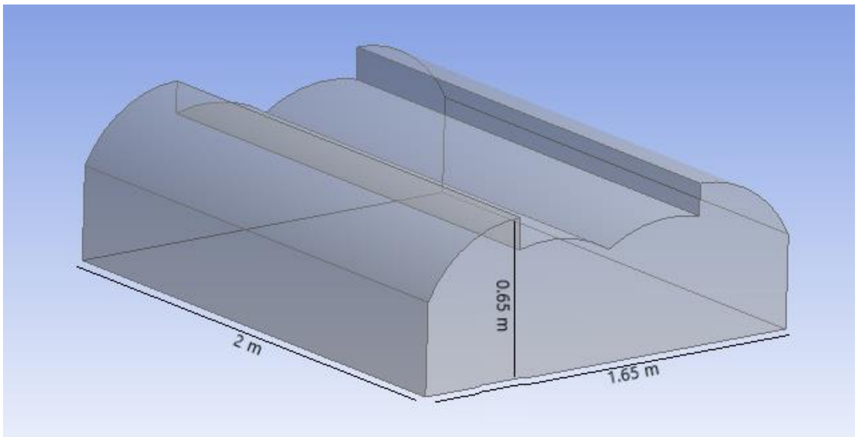


Figure III-2: The schematic of greenhouse studied

Figure III-3: Experimental setup greenhouse external view

Table III-1: Polyethylene film properties

Property	**Value**
Thickness	200 µm
Transmittance	75%
Conductivity	0.41 W/(m.K)
Diffusivity	0.2991-6 m^2/s

III.4 Measurements of different micro-climate parameters

We conducted simultaneous measurements in the two conventional and experimental greenhouses. In the experimental greenhouse we measured the temperature and the relative humidity of air inside the greenhouse in its center with a K-type thermocouple and DHT22 sensors. In parallel, in the conventional greenhouse we measured by the same types of sensors the air temperature, air relative humidity inside the greenhouse and soil temperature. The collected data from these sensors was then used to investigate the thermal behavior under different greenhouse conditions.

Table III-2 Characteristics of K-type thermocouple

Property	Description	Form
Materials	+ Lead: Chromel (Ni-Cr alloy)	
	- Lead: Alumel (Ni-Al alloy)	
Temperature Range	Continus: 0 to +1100°C	
	Short Term: -180°C to +1300°C	
Tolerance	Standard Tolerance: ±2.2°C or ±0.75%	
	Special Tolerance: ±1.1°C or ±0.4%	
Sensitivity	Approximately 41 µV/°C	

Table III-3 Characteristics of DHT22 Sensor

Property	Description	Form
Sensor Type	DHT22 (also known as AM2302)	
Temperature Range	-40°C to +80°C ±0.5°C	
Humidity Range	0% to 100% ±2% RH	
Operating Voltage	3V to 5V	
Max Operating current	2.5Ma	
Sampling Reat	0.5Hz (on reading every 2 seconds)	

III.5 Operating different systems tested

III.5.1 Low temperature management (Heating system)

The temperature of the plant surface is influenced by various heat exchanges, including convection from the air, radiation from surrounding surfaces, and latent heat exchanges through transpiration. To ensure a healthy crop with high yield and quality, growers must establish suitable climatic conditions inside the greenhouse. In semi-arid climates, winter temperatures may drop below the optimal range, posing challenges for crop growth. While heating can promote rapid growth and early maturity, it can be economically challenging due to high energy costs. Managing the ratio of heated to unheated greenhouses becomes crucial in areas where temperatures frequently fall below the biological optimum. It is essential to differentiate between heat energy generation and its distribution within the greenhouse. In horticulture, various techniques for heating greenhouses can be employed to maintain optimal conditions for crop cultivation.

In this section of the study, our primary objective was to investigate a novel heating system that harnesses the potential of solar energy and incorporates latent thermal energy storage (LTES). This research endeavors to contribute to the field by introducing the design and fabrication of a new heating system, followed by a subsequent implementation in a greenhouse prototype. By doing so, we aimed to assess the system's efficacy in delivering sustainable and efficient heating within greenhouse environments. The heating system was constituted as following:

- Hot air solar collector
- Latent thermal energy storage unit
- description of LTES unit
- Operating system

III.5.1.1 Hot-air solar collector

The solar collector consists of a single-pass solar absorber and a single 5mm thick glass cover as shown in Figure III-4. The absorber has an inclined surface and is attached to a 3 mm thick aluminum profile painted in matte black. Its dimensions are 1.2m in length and 0.8m in width. For thermal insulation, polystyrene material is used. In this case, a 4cm thick layer of polystyrene is placed on the sides.

Figure III-4: Hot-air solar collector

III.5.1.2 Description of LTES unit

The tank used in this study is a two PVC cylindrical tubes with a diameter of 16cm in diameter and length of 1.80m as shown in Figure III-5, filled with PCM (Phase Change Material) cans a diameter of 60mm and a size of 345g (Figure III-6), placed at 29cm underground of the experimental greenhouse. To minimize pressure losses and humidity, the lower side of the two pipes is perforated;

We used a total of 24 cans, with 12 cans allocated to each channel. These cans were arranged within the two channels, with each phase change material (PCM) unit positioned approximately 150mm apart from the adjacent one, as shown in Figures III-6 and III-7. Arranging the PCM cans in the tank in this manner maximizes air contact surface with the PCM cans, resulting in efficient air circulation. This allows the PCM cans to heat up rapidly and store a significant amount of heat. At the location where the two channels meet, the outlet is connected to the solar collector as shown in Figure III-8 and III-9.

A two plastic tubes (with a diameter of 60mm) with holes that serve as outlets for releasing heated air coming out of solar collector or the tank, and distribute the heat evenly in the greenhouse, the heat distribution system is suspended at a height of 15cm near the planting (Figure III-10). The two inlet is connected to the tank outlet, other/opposite end of the two tube is closed.

Figure III-5: Installation of the two tubes under the greenhouse floor.

Figure III-6: Disposition PCM cans

Figure III-7: PCM cans with a diameter of 60mm

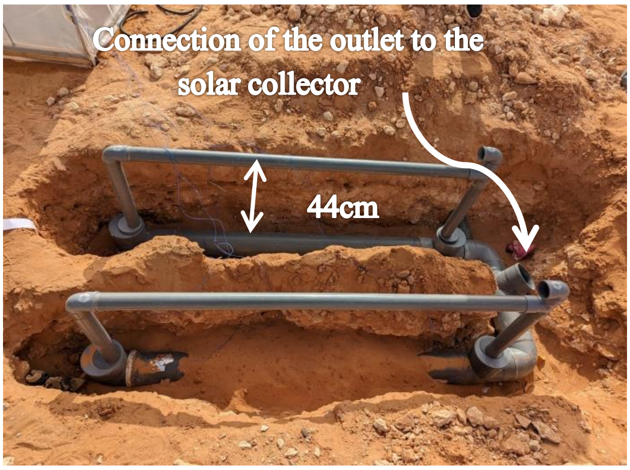


Figure III-8: Layout of the LTES unit

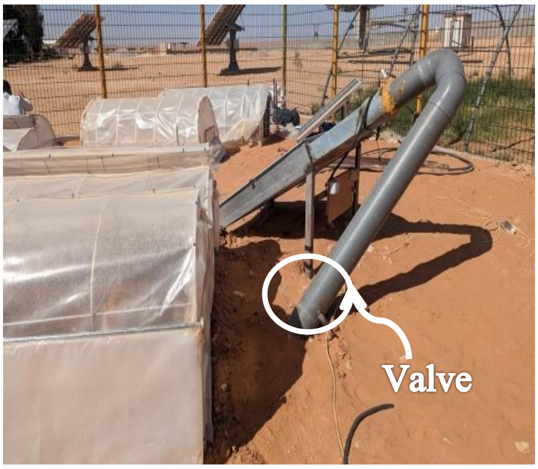


Figure III-9: Connection of the outlet to the solar collector

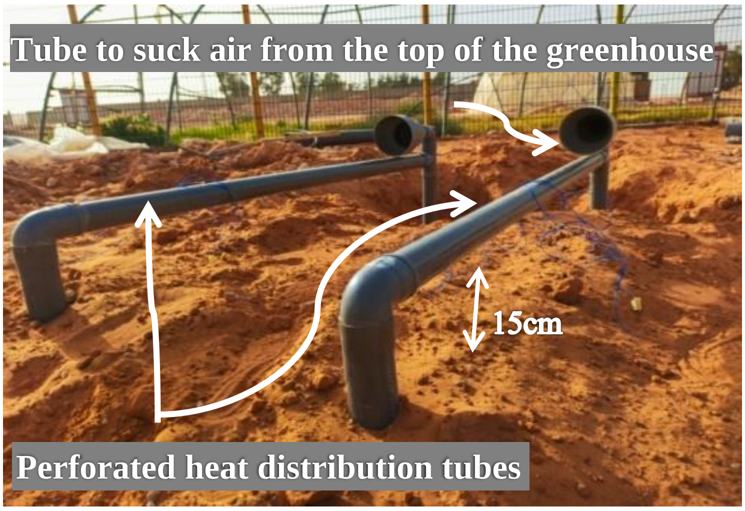


Figure III-10: LTES Unit Outlet

III.5.1.3 Thermal energy storage unit (TES)

Phase change materials (PCM) are compounds that have the capacity to store and release latent heat during a phase transformation from solid to liquid at a constant temperature. PCM materials can vary widely, including organic compounds, inorganic salts, eutectic mixtures, and Paraffin waxes, each with different characteristics and performance properties.

A. Reason of choosing chloride calcium $CaCl_2, 6H_2O$ as storage materials?

The choice of Calcium Chloride Hexa-hydrate ($CaCl_2, 6H_2O$) as a storage material for thermal energy is justified by its excellent thermophysical properties. It possesses a high heat capacity, which allows it to store a large amount of heat per unit mass. Moreover, it undergoes a phase change (solid to liquid) at a specific temperature, releasing or absorbing a significant amount of latent heat during this transition. Additionally, $CaCl_2, 6H_2O$ exhibits good thermal stability, enabling it to withstand high temperatures without degradation or undesired chemical reactions, making it a reliable option for long-term thermal energy storage applications. Furthermore, its widely availability and relatively affordable cost make it an economically viable choice for thermal energy storage systems. The thermophysical properties of the $CaCl_2, 6H_2O$ are tabulated in Table III-4. In our study, we chose to use a TES made of $CaCl_2, 6H_2O$ as our storage material. TES have been shown to be a popular and economical option for sensible heat storage. By placing the TES underground, we are able to take advantage of the large and cheap heat transfer surface provided by the earth. We utilized 24 soda cans field with storage materials withe size 345g (Figure III-11), which have rapid heat transfer, high energy storage capacity, high thermal conductivity, low cost, and long life.

Figure III-11: Cans of chloride calcium $CaCl_2, 6H_2O$

Table III-4: Thermo-physical properties of Calcium Chloride hexahydrate ($CaCl_2, 6H_2O$) [62, 63]

Propertie	Melting Point (°C)	Density g/cm³	Latent Heat of Fusion (kJ/kg)	Specific Heat Capacity (J/kg·k)	Thermal Conductivity (W/m·K)
Value	29	1.71	170	1460 (solid)	1.09 (solid)
				2130 (liquid)	0.54 (liquid)

B. Preparation of low ($CaCl_2, 6H_2O$) content salt hydrate phase change materials ($CaCl_2, 2H_2O$):

Calcium chloride, with the chemical formula $CaCl_2$ (M = 111 g/mol), exists under standard thermodynamic conditions as a white solid (molten or anhydrous Na-Cl). It is also found in the form of crystallized or hydrated calcium chloride, $CaCl_2, 6H_2O$ (M = 219 g/mol). It is easily soluble in water and alcohol. This compound is a powerful hygroscopic substance, meaning that in the presence of water, it reacts to form a hydrate while releasing heat. The reaction of hydrated calcium chloride with water involves combining 190g of calcium chloride with 200g of water. The mixture of hydrated calcium chloride and water is then placed in a closed flask, ensuring homogeneity and continuous agitation at a temperature of 120°C. Figure III-12 illustrates the amount of calcium chloride and distilled water used in the experiment.

After the completion of the reaction, the prepared product is poured into 33 cl cans (Figure III-13(a, b)).

Figure III-12: Quantity of calcium chloride (190g) and distilled water (200g)

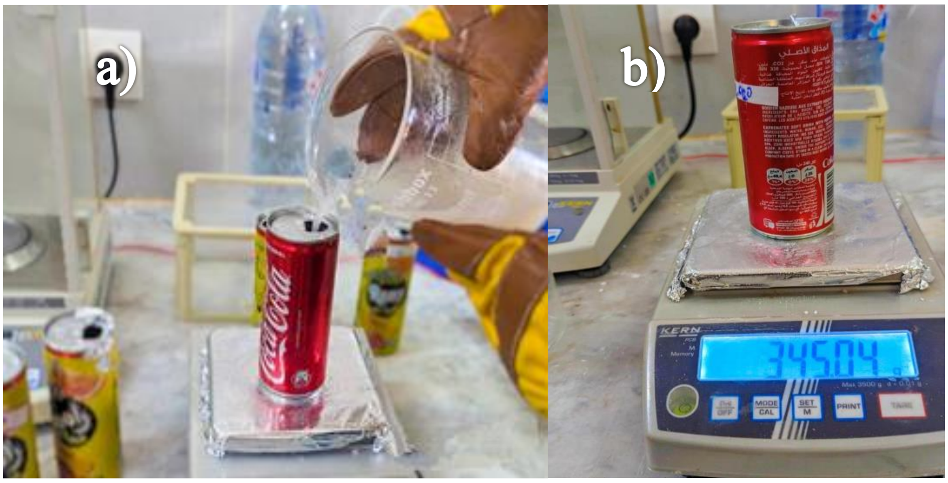


Figure III-13: a) Pouring the mixture of hydrated calcium chloride into the cans.
b) PCM cans mass (g)

Figure III-14: Final state

Table III-5: Melting Temperatures of the Obtained Materials and $CaCl_2, 6H_2O$

Obtained products.	$CaCl_2, 6H_2O$
Melting temperatures (°C)	29

These experiments are translated based on the following reactions:

$$(CaCl_2, 2H_2O) + 4H_2O = (CaCl_2, 6H_2O)aq + \text{Release of heat} \qquad \textbf{(Eq.III.1)}$$

III.5.1.4 Functioning principle of the combined solar heating system

The operating principle of the combined solar heating system utilized in this study is illustrated in Figure III-15. In this system, phase change material (PCM) in the form of $CaCl_2, 6H_2O$ with a melting temperature of 29°C was employed as the thermal energy storage unit. The temperature inside and outside the greenhouse was measured and collected at different locations every minute through twelve temperature sensors (K-type thermocouple). The sensor layout is shown in the figure below. Inlet/outlet fans of the NMB-4715MS type (Figure III-16), with a power rating of 14/15W and an airflow of 102m³/min, are used for air circulation purposes.

During the daytime, the system operates by using fan1 to draw the hot air generated by the solar collector. This hot air is then directed into the latent thermal energy storage (LTES) unit, serving two purposes. Firstly, it provides heating for the greenhouse by distributing the hot air throughout the space. Secondly, the hot air is also directed to charge the PCM, enabling it to absorb and store the thermal energy for later use. This dual functionality ensures effective utilization of the solar energy for immediate heating needs while simultaneously storing excess thermal energy in the PCM for subsequent use.

During nighttime, when the temperature inside the greenhouse decreases, the heat stored in the PCM is released. This heat is then distributed using perforated tubes, allowing for controlled and efficient delivery of warmth throughout the greenhouse. This nocturnal heat release from the PCM units ensures an uninterrupted heat supply, thereby creating a favorable environment for plant growth during the night hours.

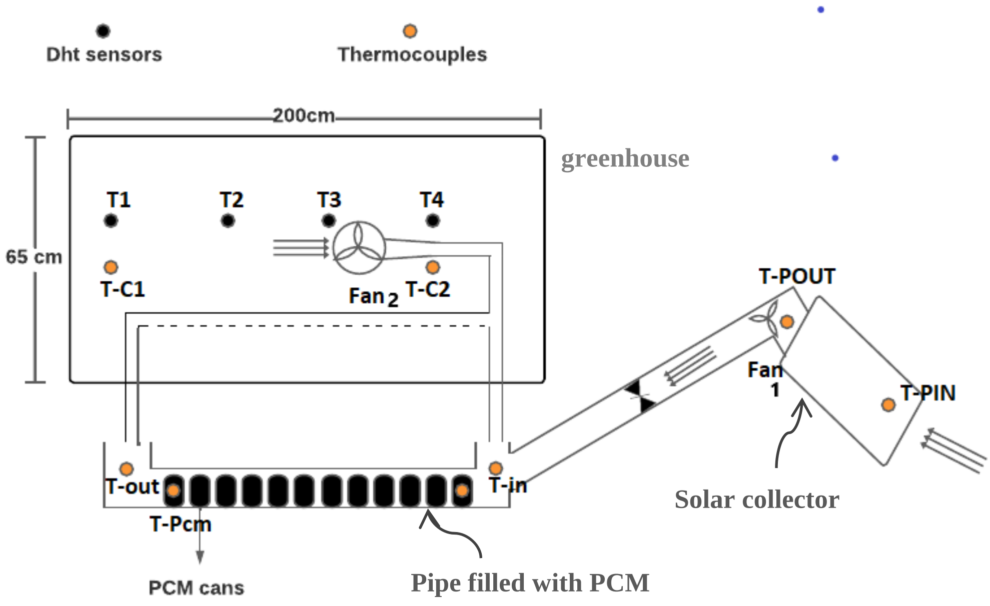


Figure III-15: Schematic view of the combined solar heating system

Table III-6: Temperature Measurements using Thermocouples in the Experimental Setup

Thermocouples	Measure
T-PIN	Measure the absorber temperature (Tabs)
T-POUT	Measure temperature outlet of the solar collector
T-in	Measure temperature inlet of the storage system
T-out	Measure temperature outlet of the storage system
T-Pcm	Measure temperature inside PCM cans
T-C1	Measure indoor greenhouse temperature
T-C2	Measure indoor greenhouse temperature

Figure III-16: fans used to draw air from the greenhouse.

III.5.2 High-temperature management:

III.5.2.1 Natural ventilation system

A greenhouse's effectiveness depends on a number of variables, including the selection of the right plant species and placement in relation to sunlight. Variations in temperature, moisture content, and airflow within the greenhouse are also significant. Ventilation is one of the crucial components of a greenhouse that influences these and other variables. It could be argued that optimizing ventilation is the key to ensure a productive greenhouse.

A. Operating of natural ventilation system

The natural ventilation system incorporates two side openings and two openings located at the top of the roof, the ventilation system designed are shown in Figure III-17 (a, b).

To controlling the vents, a system of an electric gear-motor and pulleys is employed. The system basically consists of wrapping/unwrapping the plastic wall on itself to retrieve or deploy as needed. An electric gear-motor (one shaft), depicted in Figure III-18 is responsible for driving the movement of the pulleys, which in turn manipulate the opening and closing of the vents. Steel pipe serves as the vent bottom bracket and at the same time it rotates and wraps/unwraps the plastic upon itself while going up or down. Finally, the wire ends embedded in the other end. The data-sheet of the electric gear-motors used for the natural ventilation system is shown in Table III-7.

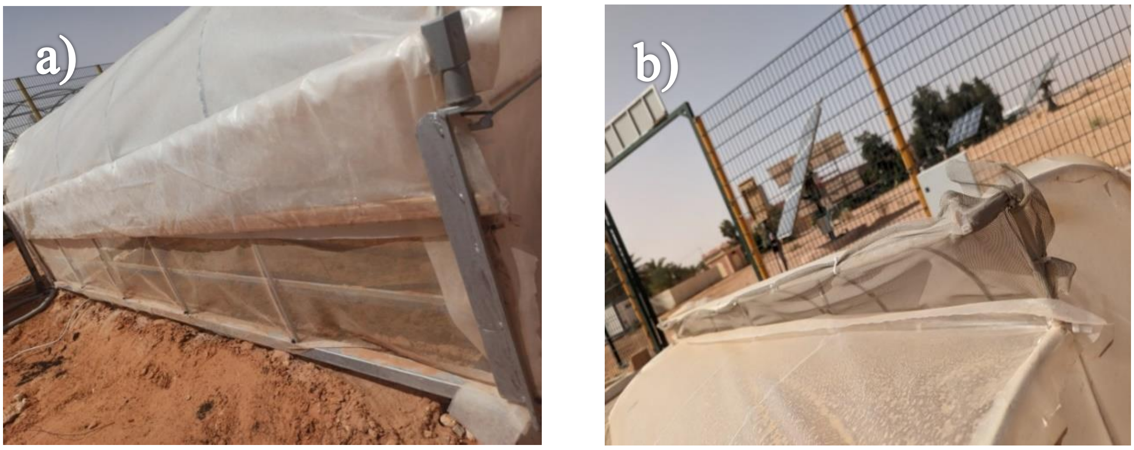


Figure III-17: Greenhouse vent configuration showing, a) sidewall roll-up, b) roof flap vent

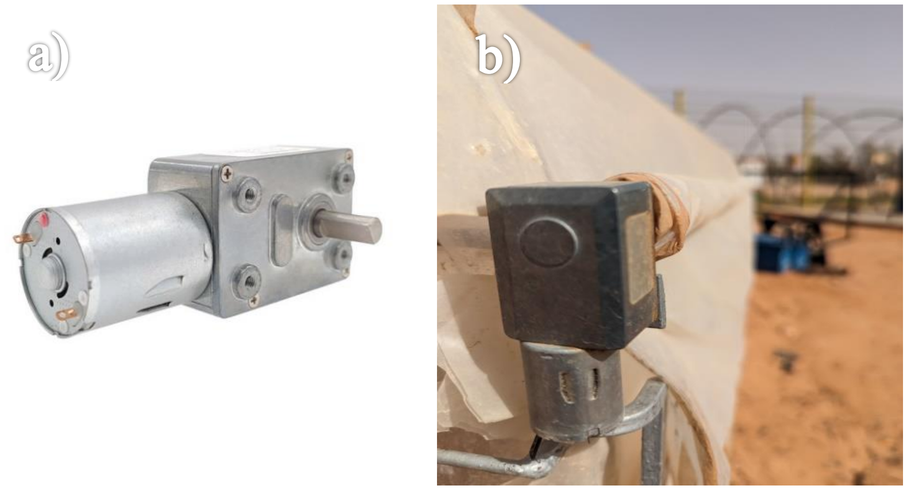


Figure III-18: a) JGY-370 Motor (one shaft), b) Gear-motor installation,

Table III-7: Electric JGY-370 Gear-motor Data-sheet.

Torque:18Kg.cm	**Usage:** Boat, Car, Bicycle, Electrical, Fan, etc…
Model Number: JGY-370	**Puissance de sortie:** 15 w
Continuous current (A): 0.6A	**Caractéristique de protection:** Anti-drop
Rated voltage (v): 6v,12v,24v	**Construction:** PARMANENT MAGNET
Switching: Brush	**Type:** Gear Motor
Efficiency: IE 1	**Origine:** CN (Origin)
Certification: ce	

III.5.2.2 Shading system

Shading nets are widely used in greenhouses to regulate sunlight, prevent excessive heat, enhance crop quality, and avoid water stress. Utilizing shading nets alongside natural ventilation is an effective method to cool greenhouses during the summer. This approach not only helps reduce the need for energy-intensive fan-pad cooling systems but also minimizes water consumption for irrigation. Shading nets offer a popular and efficient solution for achieving optimal growing conditions and resource efficiency in greenhouse cultivation.

One greenhouse was kept without shading (control) and the other was shaded using two horizontally placed white plastic net (50% shading) below the roof at a height of 0.60 m, where each net covers an area with dimensions of 0.70 m width and 2 m length and vertically inside the side-walls using the white net. Figure III-19 represents the outside and onside View for Shading System.

In this system, a double shaft gear-motor (depicted in Figure III-20(a, b)) is employed, which shares the same technical properties as the gear-motor used in the natural ventilation system, are connected directly to the shafts through bearings, where the mesh is rolled (Figure III-19(c, d)). This axis forms the framework on top of the system and, at the other end of the shade mesh that goes up or down, there is a copper pipe that serves as a weight-guide and rests on three copper rails (Figure III-19(d)). The shading net is used to cover the roof of the greenhouse from 8:00 until 16:00 hours on sunny days, and should be opened on cloudy days.

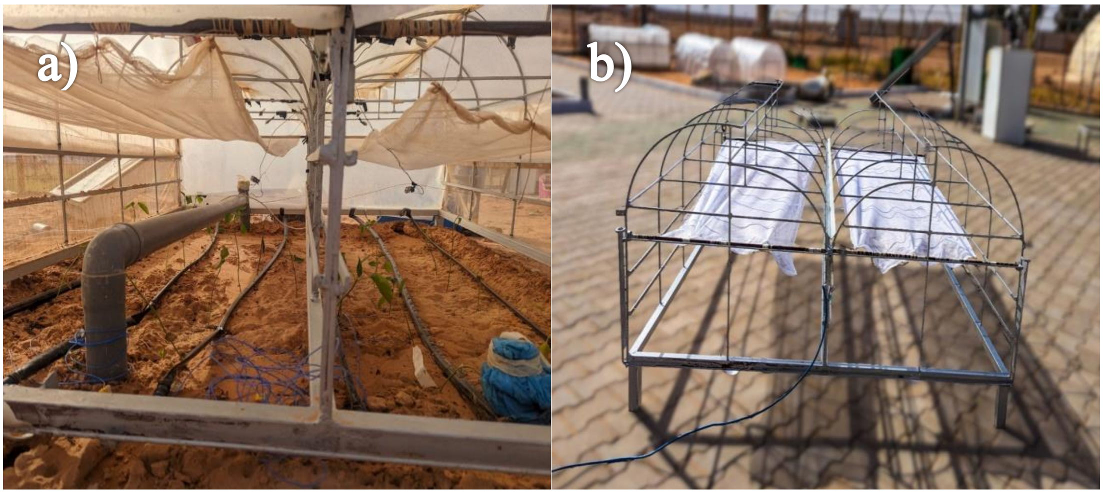


Figure III-19: Shading System: a) Onside view, b) Outside View

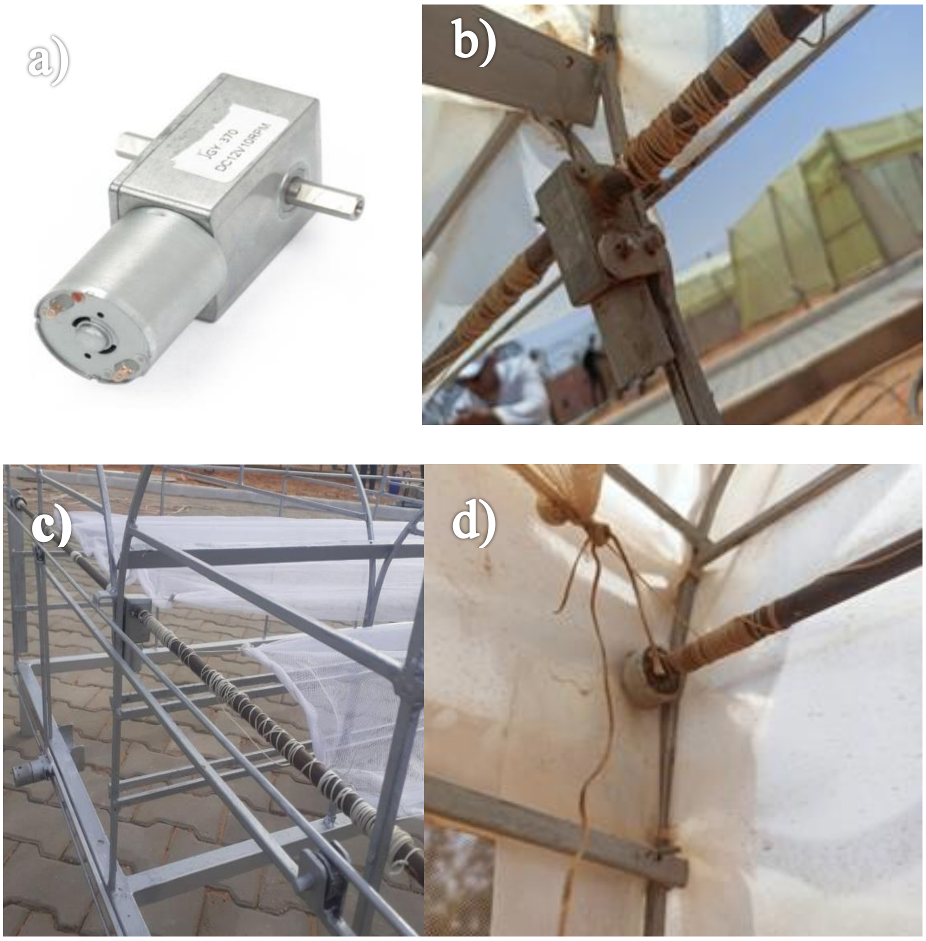


Figure III-20: Shading system: **a)** JGY-370 double shaft Motor,

b) Gear-motor installation, **c)** Copper pipe, **d)** Pulley

III.5.2.3 Cooling system

An experimental study was conducted to investigate the temperature and humidity gradients that occur within a greenhouse when a Fan-Pad cooling system is utilized in Ghardaia conditions. The performance parameters of the cooling system were determined using psychometric calculations based on external and internal data collected from the greenhouse environment. This study aimed to assess the effectiveness of the Fan-Pad system in maintaining favorable temperature and humidity levels for plant growth and to understand the distribution of these parameters within the greenhouse space. The results of this study will contribute to improving the design and operation of greenhouse cooling systems in similar climatic conditions, ultimately enhancing the overall productivity and quality of crops grown in these environments.

During the experimental study, internal shading screens were installed within the greenhouse to control the amount of sunlight entering the space. Additionally, both the side windows and top windows of the greenhouse were closed, preventing any external airflow from entering or exiting. These measures were implemented to create a controlled environment and isolate the effects of the Fan-Pad cooling system on temperature and humidity gradients within the greenhouse.

A. Components and their functions in a Fan-Pad cooling system

A direct evaporative cooler, is indeed a simple and effective device for cooling air through the process of evaporation. It operates based on the principle that when water evaporates, it absorbs heat from the surrounding air, resulting in a cooling effect. The fan-pad evaporative cooling system was applied in the experimental greenhouse.

The fan-pad cooling system, as shown in Figure III-21, contains the following elements

- **The cover:** constructed from burlap material (Figure III-22(a)), envelops the internal components of the system, providing a protective enclosure. This burlap cover serves the purpose of safeguarding the palm leaf from external elements and potential damage. Additionally, it helps to maintain the integrity of the system by preventing the ingress of dust, debris, and other contaminants. The durable and breathable nature of burlap makes it an ideal choice for this protective cover, ensuring the functionality of the water distribution system.
- **Filter Media:** A highly wet table porous material is made from palm leaf, has a thickness ranging 2 inches, and they are kept moist by water continuously dripping onto their upper edges.
- **Evaporative cooling pad:** also known as a wet pad is a key component in evaporative cooling systems. which placed an evaporative pad (120 cm · 4 cm · 40 cm) as seen in Figure III-22(a), on the air inlet at the east end at 10 cm above from the ground.
- **Blower Fan:** The described system includes two large blower fans, each operating at a voltage of 12V and consuming 50Kw of power (Figure III-22(b)). These fans are installed inside the housing and are used to draw in warm air from the outside. Afterward, the fans push the cooled and humidified air into the greenhouse.

- **The water distribution system:** incorporates two perforated tubes, positioned above the filter media as depicted in Figure III-22(a). These tubes play a crucial role in evenly dispersing water across the entire surface of the pad. This careful distribution mechanism guarantees that the filter media maintains a consistent and optimal saturation level, thereby facilitating efficient cooling. By ensuring uniform water distribution, the system maximizes the effectiveness of the evaporative cooling process, ultimately enhancing its cooling capabilities.
- **The water collection tube**: is located at the bottom of the evaporative cooling pad. Its primary function is to collect and channel any excess water, as well as impurities or sediments that have passed through the pad during the evaporation process. This tube ensures that the water is effectively collected and prevents it from pooling or causing damage to the pad or surrounding areas. The water collected in the pipe is directed to the tank using a pump in order to be recycled back into the system for further use.

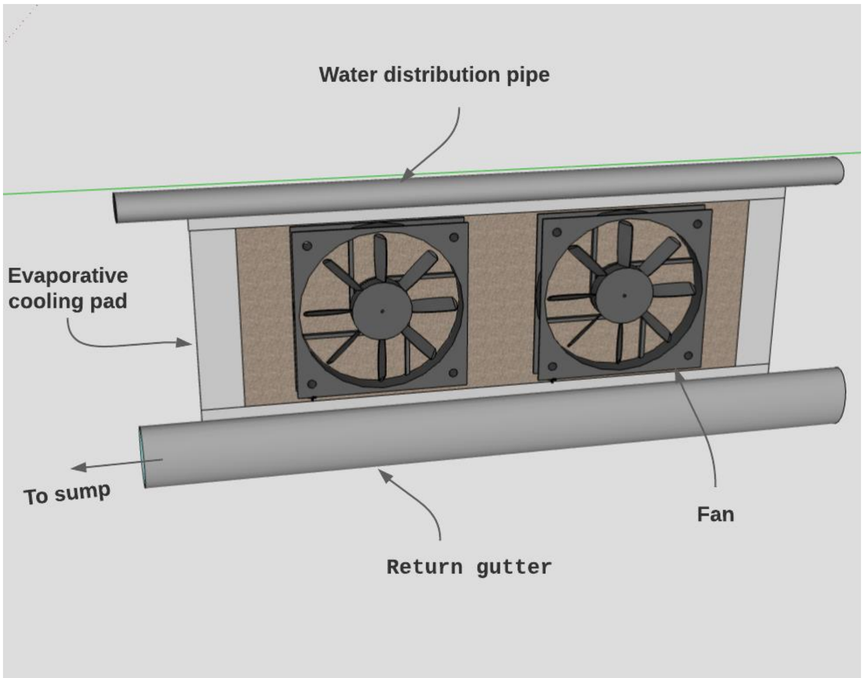


Figure III-21: Fan-pad cooling system design

Figure III-22: components of Fan-Pad cooling system: a) Evaporative cooling pad, b) Fan, c) Palm leaf, d) Arranging palm leaf inside an evaporative cooling pad.

B. Operating of Fan-Pad cooling system

A fan-pad system works on the principle of evaporation, after closing all openings and doors while the fans are running, water flows along the two distribution pipes and drains down into the pad material. Outside air is drawn through the filter media by the two fans. As the air passes through the wet pad, water evaporates from the pad's surface into the air, absorbing heat from the warm air and reducing its temperature. The cooled air is then blown into the greenhouse, providing a refreshing and cooler environment inside.

Figure III-23: the external view of an experimental fan-pad cooling system.

C. Measurement and collected data

Temperature and relative humidity were recorded by using DHT22 sensors placed at different locations inside the greenhouse, all these temperature and relative humidity sensors were connected to the data logger system placed outside of the double-span greenhouse. The sensors layout is shown in Figure III-24.

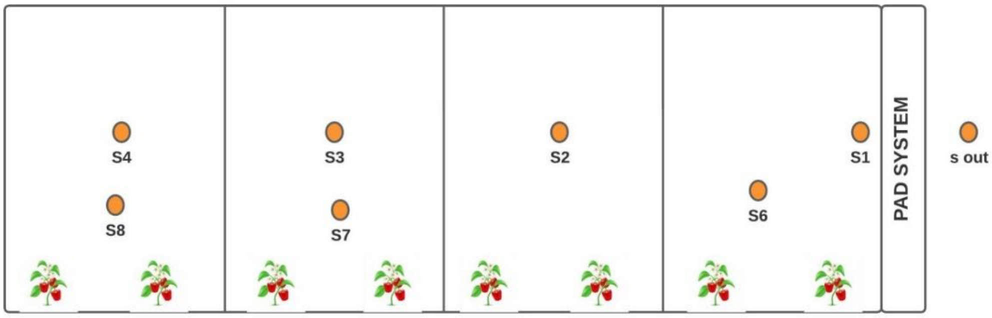


Figure III-24: The position of the sensors in the fan-pad cooling system

III.6 Thermal analysis of greenhouse

In order to analyze the greenhouse climate, the energy balance equations for different components (cover, canopy, soil and inside air) of the greenhouse system with following general assumptions are made:

III.6.1 Heating system

III.6.1.1 Performance of solar collectors

Thermal collector efficiency is defined as the ratio of useful energy and the incident solar radiation, can be calculated by the following equation: [64, 65]

$$\eta_c = \frac{Q_c}{A \cdot G_h} \qquad \textbf{(Eq III-1)}$$

The useful energy Q_c used in the calculation of collector efficiency can be estimated by using following equation: [66]

$$Q_c = \dot{m}_{air} \cdot Cp_{,air} \cdot (T_{\text{in}} - T_{\text{out}}) \qquad \textbf{(Eq III-2)}$$

Where:

Q_c: Energy collection;

A: surface area (m^2);

G_h: global solar radiation (W/m^2);

m: mass (kg);

Cp: Air specific heat (J. kg^{-1}). K^{-1});

T_{in}/T_{out} : Inlet/Outlet temperature (°C);

III.6.1.2 Performance of LTES unit

In LTES unit, the transferred heat can be calculated instantaneously with the following equation [64]. The heat transfer during the charge and discharge of the phase change material is a function of time.

$$Q_{PCM(t)} = \dot{m}_{air} \cdot Cp_{,air} \cdot (T_{in} - T_{out}) \qquad \textbf{(Eq III-3)}$$

Where:

$\dot{m}$: mass flow (kg. s^{-1});

$Cp_{,air}$: Air specific heat (J. kg^{-1}). K^{-1});

T_{in}/T_{out} : Inlet/Outlet temperature (°C);

III.6.1.3 Heating requirements of the greenhouse

All of the greenhouse's walls are closed at night. As a result, the internal air acts as a closed thermodynamic system that interacts with the external environment, exchanging energy. The energy requirements ($Q_{h,r}$) of greenhouse inside air to maintain its nocturnal temperature at the optimum value of tomato growth (12 °C) are calculated as follows: [67]

$$\mathrm{Q_{h,r}} = \sum_{\mathrm{t(t_{in}<T_{op})}}^{\mathrm{t(t_{in}\geq T_{op})}} \mathrm{m_a c_a (T_{op}(t) - T_{in}\ (t))} \qquad \textbf{(Eq III-4)}$$

Where:

m_a: are the air mass inside the greenhouse, 742.5 kg;

c_a: specific heat of air at 25 °C, 1005 J/kg. K;

$\mathrm{T_{op}(t)}$ and $\mathrm{T_{in}}$ (t) are optimum temperature of tomato growth and the inside temperature, respectively.

III.6.2 Cooling system

III.6.2.1 Pad Efficiency

The cooling efficiency of the pad can be calculated by the following equation: [51]

$$\eta = \frac{\mathrm{T_{in}} - \mathrm{T}_{out}}{\mathrm{T_{in}} - \mathrm{T_{wb}}} \qquad \textbf{(Eq III-5)}$$

Where:

η: is the cooling efficiency;

$\mathrm{T_{in}}$: the inlet air dry bulb temperature (°C);

$\mathrm{T_{out}}$: the supply air temperature (°C) after passing through the cooling pad;

$\mathrm{T_{wb}}$: the inlet air wet bulb temperature (°C).

III.7 Conclusion:

In the chapter that is now concluded, a comprehensive description of the experimental equipment, instruments, and fixtures used to conduct the experimental tests within the scope of this research was presented. The selection of appropriate materials was crucial to ensure the accuracy and reliability of the obtained results. Additionally, the Methods section outlined the step-by-step procedures followed during the experiments and data collection. It highlighted the design and selection of different materials used in an HVAC system, as well as the data collection methods.

In the next chapter, we will proceed with the presentation and discussion of the results obtained.

Chapter IV: Results and discussion

IV.1 Introduction:

The final chapter of this master's thesis encompasses the results and discussions obtained from three experiments conducted on two experimental greenhouse setups: the experimental greenhouse and the control greenhouse. The experiments focused on two main systems: heating and cooling. Within these systems, various components such as shading, cushions, and fans were utilized. The detailed descriptions of these systems, along with the materials and methods employed, have been previously discussed in the chapter titled "Materials and Methods."

In this concluding chapter, we will delve into the outcomes of these experiments and engage in an in-depth discussion regarding their implications. The results obtained from each experiment will be presented, analyzed, and compared to draw meaningful conclusions. Additionally, we will examine the effectiveness and efficiency of the heating and cooling systems implemented in the experimental greenhouse.

The first experiment concentrated on the heating system, aiming to evaluate its performance under different conditions. Factors such as temperature variations, energy consumption, and thermal stability were closely monitored and analyzed. By scrutinizing the collected data, we will assess the efficiency of the heating system and its ability to maintain the desired temperature levels within the experimental greenhouse.

Moving on, the second experiment focused on the cooling system, which incorporated shading, cushions, and fans. The goal was to investigate the cooling efficiency of these components individually and in combination. The impact of shading on temperature reduction, the effectiveness of cushions in preserving coolness, and the role of fans in promoting air circulation will be examined. The findings from this experiment will be crucial in determining the effectiveness of the implemented cooling system and its potential for practical applications.

By comparing the results from the heating and cooling experiments, we will be able to identify the strengths and weaknesses of each system. Furthermore, we will explore potential synergistic effects when integrating both systems within the experimental greenhouse. The discussion will revolve around the optimization of energy consumption, the achievement of ideal temperature ranges, and the overall sustainability and cost-effectiveness of the greenhouse operation.

This final chapter serves as a comprehensive analysis and evaluation of the experimental outcomes, providing a solid foundation for future research and advancements in greenhouse technology.

IV.2 The heating system

IV.2.1 Effect of solar radiation

The experiment was conducted over five days, starting at 7:00 AM on April 5th and ending at 11:59 PM on April 9th. Figure VI-1 shows the relationship between temperature changes in the solar collector absorber plate and changes in solar radiation over three days. Measurements were taken in Ghardaïa. On the first day, after sunrise, global solar radiation started to increase and reached its peak around 2:00 PM, surpassing 1000 W/m². This indicates a significant level of solar energy reaching the collector. On the second day, the radiation level dropped to 900 W/m². The third day was marked by some disturbances in radiation due to cloud cover, with values fluctuating but still reaching a maximum of 1000 W/m².

The temperature of the absorbent plate showed direct correspondence with the solar radiation curve. The highest temperature was recorded during the experiment on the third day and amounted to 93 °C, while the lowest temperature was recorded during the night of this day, when it decreased to 3 °C. This confirms the direct relationship between solar radiation and temperature dynamics of the absorber plate.

These results, together with the specific solar radiation and temperature data, provide valuable insights into the performance and behavior of the solar collector system. They contribute to understanding and improving the use of solar energy, particularly in regions with similar environmental conditions.

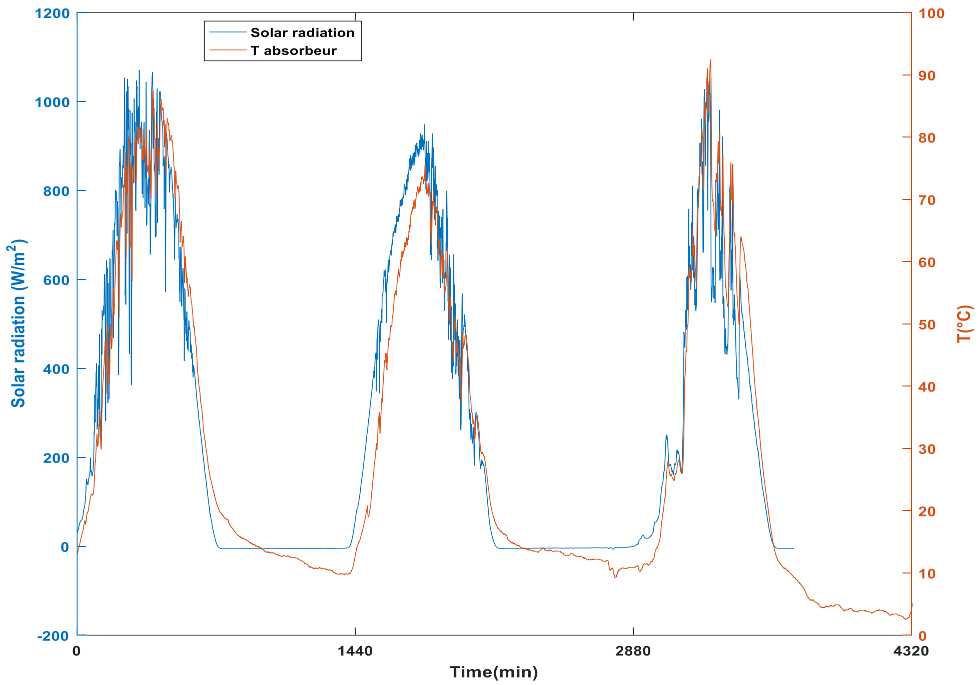


Figure VI-1: Relationship Between Global Solar Radiation and Absorber Plate Temperature

IV.2.2 Performance of solar collectors

The experimental setup utilized T-type thermocouples for temperature measurements of the air entering and exiting the collector, as well as the ambient temperature. The thermocouple measuring the ambient temperature was placed in a shelter to shield it from direct sunlight. The mass flow rate of the air was calculated based on the measured air velocity at the collector inlet and outlet.

The aim of this research study is to conduct an experimental investigation of the thermal performance and efficiency of the collector. The collected experimental data were analyzed to generate efficiency curves for the system. Thermal collector efficiency, which represents the ratio of useful energy to incident solar radiation, served as the primary metric assessment. The collector efficiency calculation involved estimating the useful energy (Q) using the equation mentioned in the previous chapter.

Incident solar radiation is widely recognized as a critical factor for collector efficiency. The temperature of the absorbent surfaces shows an increase of up to 90 °C in response to the incident solar radiation. Moreover, the ambient air outside the system has a temperature of up to 50 degrees Celsius. The results shown in Figure IV-1 reveal a clear trend: collector efficiency climbs with higher mass flow rates of the working fluid. It is worth noting that the collector achieves maximum efficiency when the incident solar radiation reaches its peak.

In Figure VI-2 illustrates the comparison between the useful energy generated by the solar collector and the energy incident on the glass surface (A*I) of the collector with an area of 0.96 square meters. The calculated compound efficiency was found to be 70%. Although negative values representing energy loss from a pipe responsible for transporting warm air at night were calculated, the total energy gain for the solar collector was 64,147,859.12 joules (J).

Note: The reason for the worthless energy that falls on the glass surface on the fourth day is the inability to measure the value of solar radiation.

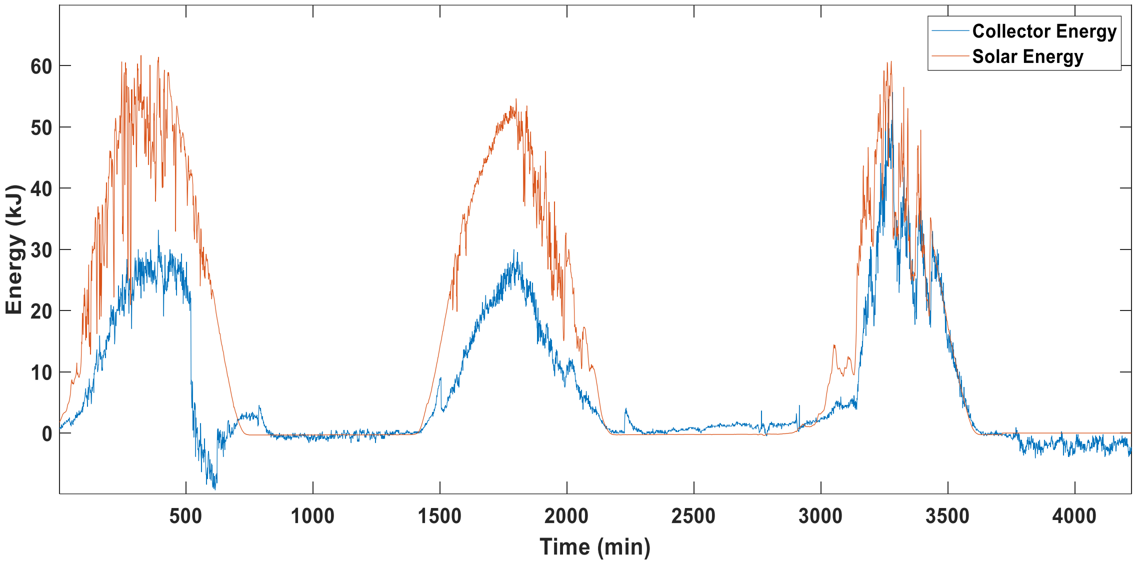


Figure VI-2: Comparison of Useful Energy and Incident Energy on the Glass Surface of Solar Collector

IV.2.3 Effect of phase change materials

The experiment spanned five days, commencing at 7:00 AM on April 5th and concluding at 11:59 PM on April 9th. Figure 4.2 provides a comparison between the indoor air temperature of the experimental greenhouse and the air temperature inside the twin greenhouse.

On April 5 and 9, in sunny weather, both greenhouses experienced their lowest temperatures around 7:00 AM. The PCM greenhouse recorded a temperature of 13.3 °C, while that of the normal greenhouse was 11.9 °C. As the sun rose, there was an increase in the indoor air temperature due to the effect of solar radiation, reaching maximum values of about 39 °C and 37.1 °C for the PCM greenhouse and the regular greenhouse, respectively.

During the afternoon from 2:00 PM to 7:00 PM, a significant drop in temperature was observed in both greenhouses due to the decrease in solar radiation. After sunset, the rate of temperature decrease slowed down, causing a gradual decrease until it reached the lowest recorded values of 12.1 °C and 10.8 °C, respectively. Similar patterns were seen on the last day, with slight differences due to solar radiation.

On the 6th and 8th of April, which were characterized by less solar radiation than the first day, but there was no significant difference, a decrease in the external air temperatures was observed in general. However, there were notable differences in the minimum and maximum temperatures between the two greenhouses, ranging between 4.7 °C and 7.5 °C during the day. In addition, there was a difference of 1°C to 2.5°C in the lowest temperatures recorded overnight.

The third day was marked by a decrease in the outside temperature (cold day), resulting in the lowest high temperature and the lowest maximum temperature observed during the five-day experiment. While there was a slight difference of 1 °C between the highest temperatures recorded in the greenhouses, a difference of 2.5 °C was observed between the lowest temperatures.

In summary, the temperature regulation of the PCM greenhouse was found to be superior to that of the normal greenhouse throughout the experiment, considering day-night temperature fluctuations rather than relying solely on solar radiation as an influencing factor.

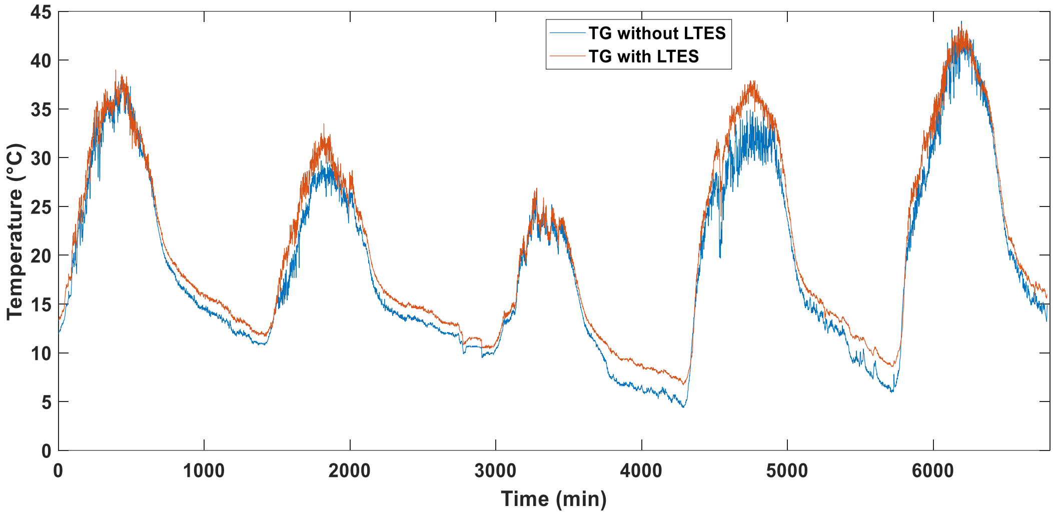


Figure IV-3: shows the differences in air temperature inside two greenhouses. The incorporation of phase change materials (PCMs) into the heating system facilitated the experimental investigation.

To evaluate the effect of phase change materials (PCMs), three thermocouples were placed inside the PCM, and the temperature values obtained from each location are shown in the Figure IV-4 Significantly, the T1G, located inside the first can in the left tube, showed higher temperatures during the day and lower temperatures during the night than the other enclosures. This disparity can be attributed to its placement at the inlet of the tube, which exposes it to the warm air emitted from the solar collector during the day. However, during the night, the temperature drop is attributed to the heat exchange between the greenhouse and the PCM. In contrast, T2T and T3R were placed at different locations in cases located deep in the two tubes, which showed a temperature difference of up to 2.5 °C. The T3R capsule, located in the last canister in the right tube, was subjected to minimal thermal turbulence, and temperatures were maintained in the range of 19 to 27 °C. This can be attributed to its location, which is less prone to hot air flow.

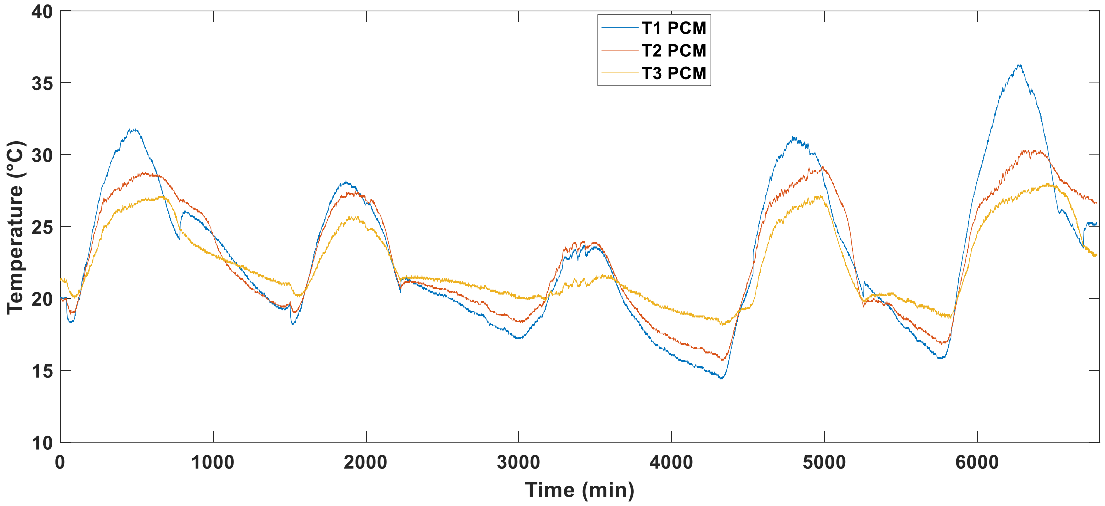


Figure IV-4: Thermometers are in various positions within the tubes of a phase change material.

The presented graph, denoted as Figure IV-5, illustrates the temperature difference between the air inside and outside the tube containing the phase change material over a period of 5 days. Upon analysis, it is observed that the temperatures of the air entering the phase change material tube and exiting from the solar collector outlet are significantly high during the daytime, reaching a maximum of 44 degrees Celsius. Conversely, these temperatures are considerably low during the nighttime, dropping to as low as 10 °C on the third day. In contrast, the outside air temperatures remain relatively stable, ranging between 20 and 30 °C, providing an ideal environment for plant growth.

This outcome aligns with previous research highlighting the effectiveness of utilizing phase change materials in temperature stabilization and maintaining suitable conditions during nighttime. It serves as further evidence supporting the benefits and efficacy of employing phase change materials in greenhouse applications.

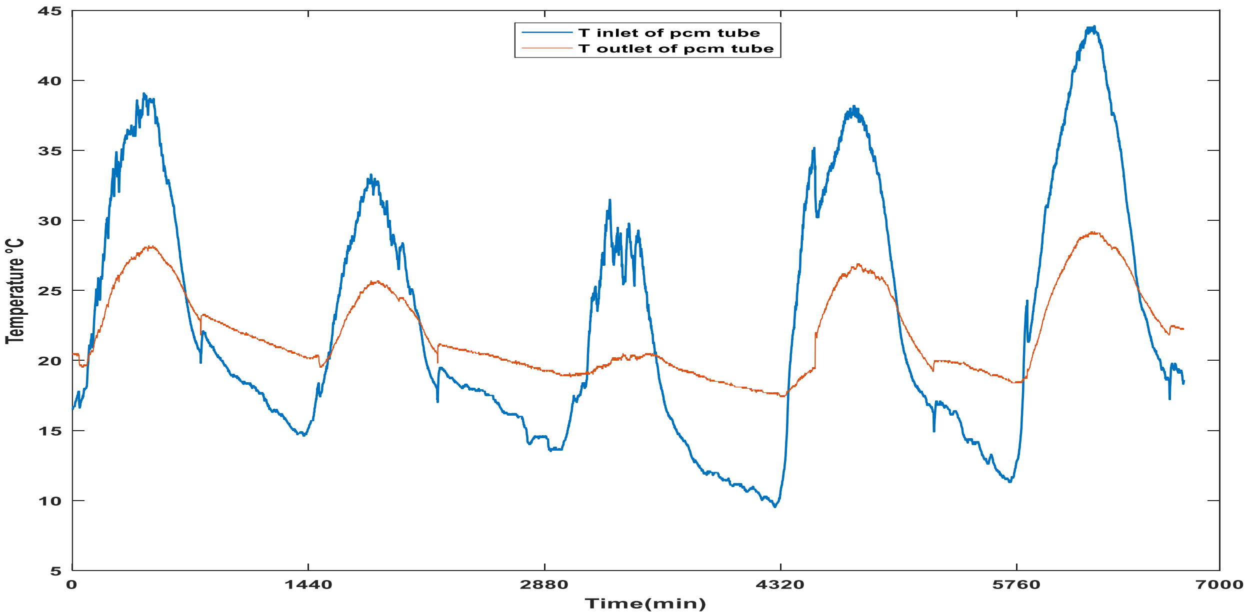


Figure IV-5: The difference between the temperature of the air entering and leaving the tube of a phase change material

Figure IV-6 depicts the temperature variations between the experimental greenhouse and the outside air, along with the temperatures of the phase change materials (PCMs). It is notable that during the day, the temperature difference between the greenhouse and ambient temperatures exceeds 10 °C, while during the night period, this difference is reduced to 2.5 °C. Furthermore, the temperatures of the phase change materials fall within the range of 20 to 35 °C, demonstrating a significant deviation from the external temperatures, which hover around 10 °C. These findings reinforce our earlier observations regarding the effectiveness of phase change materials in mitigating temperature fluctuations. They absorb heat during the day and release it at night, aiding in the stabilization of temperatures within the greenhouse.

Consequently, these results provide valuable insights into the performance and efficacy of the heating system, particularly its capacity to regulate and maintain optimal temperatures within the greenhouse.

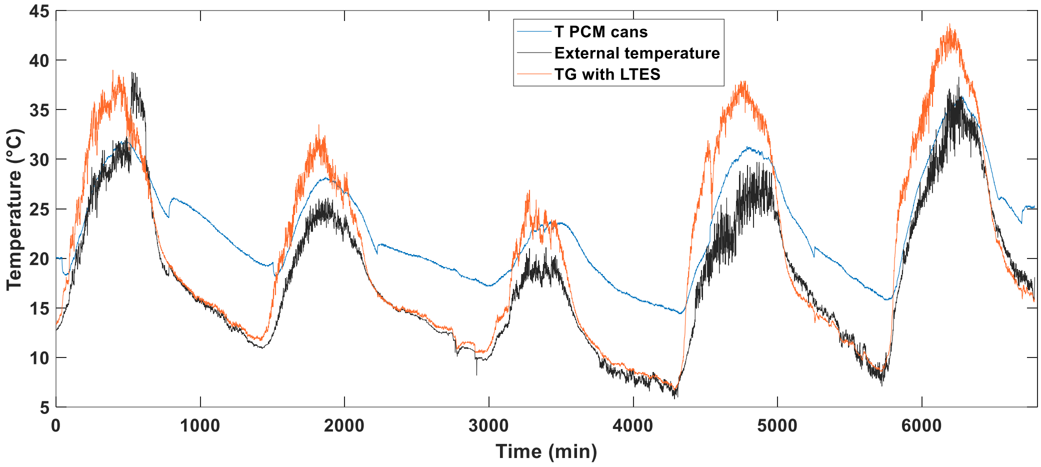


Figure IV-6: The difference between the ambient temperature and the air temperature inside the experimental greenhouse in addition to the temperature changes of the phase change material.

The graph (Figure IV-7) illustrates the variations in required energy, stored energy, solar energy, and energy obtained from the solar collector over a period of 3 days. On the first day, it can be observed that the solar energy matches the energy required to heat the experimental greenhouse, reaching a maximum of 60 KJ. However, the energy from the solar collector decreased by 50%, equivalent to the stored energy, which reached a maximum of 30 KJ. During the night, the phase change materials released only 20 KJ of energy, indicating that we can fulfill 30% of the greenhouse's energy needs during nighttime. These values remain consistent for the last two days, with a decrease in the required energy to 45 KJ on the second day and 40 kilojoules on the third day.

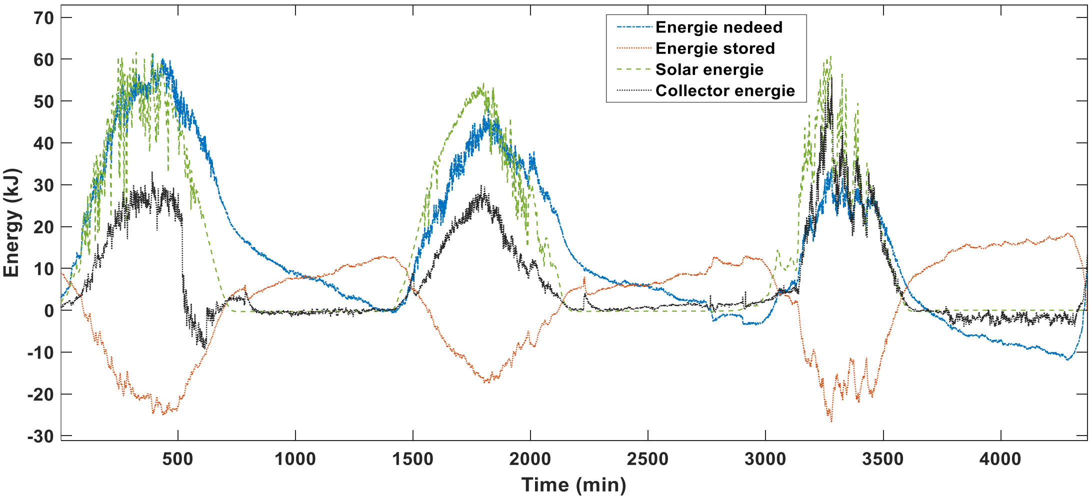


Figure IV-7: the variations in required energy, stored energy, solar energy, and energy obtained from the solar collector over a period of 3 days

IV.2.4 PCMs Saving Energy

The selection of the PCM was made based on the desired properties and the specific requirements of the greenhouse applications. The selected PCMs should exhibit safety, non-corrosion, non-toxicity, hazardousness, and odourless. In addition, the phase transition temperature must fall within the appropriate temperature range for crop growth and efficient use of latent heat.

In order to evaluate the efficiency of phase change materials (PCMs), we analyzed the average energy storage and release of the PCMs. The energy per minute was calculated so that the curve(Figure IV-8) represents the values of energy storage, released. So the color is dangerous for energy release and blue color for storage. The average energy storage during the day was determined to be 468,83535.63 joules, while the average energy release during the night was 348,50901.02 joules. Although the PCMs successfully met the thermal requirements of the greenhouse during the night, especially on the third day, which is the coldest night, it is important to stress that the experimental results indicated that the air temperatures inside the greenhouse exceeded the maximum allowable inside a greenhouse for plant growth (34°C) on days 1, 4 and 5 (Figure IV-3). This occurrence can be attributed to exceptional weather conditions, with higher outdoor air temperatures observed on these particular days. However, this problem can be easily mitigated by applying a shading system to regulate temperatures during the winter periods

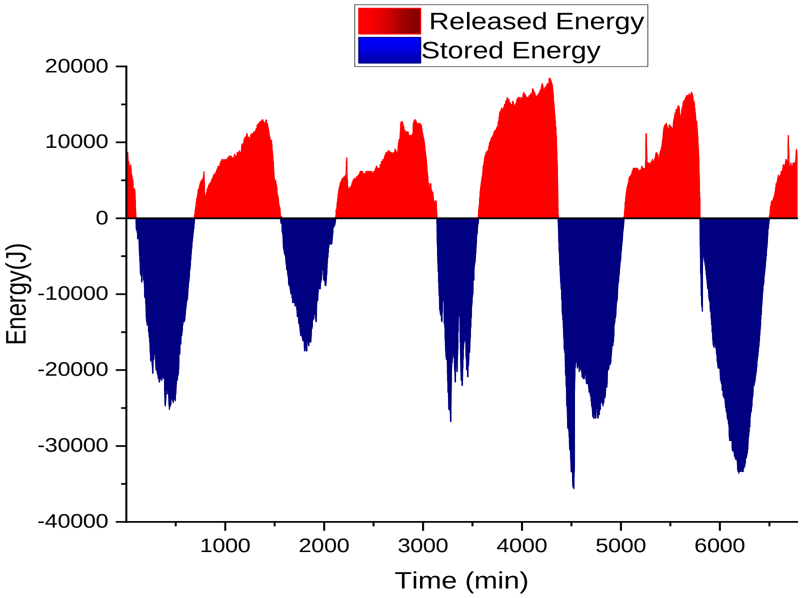


Figure IV-8: Represents the values of energy storage, released of PCM.

IV.3 The shading system

Coinciding with the onset of summer, the second experiment took place in the same location and using the same two greenhouses. We replaced the heating system with a cooling system using shading during the days 12, 13, 14, 18, 19 and 20 May 2023. Despite the simplicity of the system, it was effective in reducing temperatures. Inside of the experimental greenhouse. The difference between the experimental greenhouse and the twin greenhouse exceeded 6 degrees Celsius during the experiment period. So, on the first day, the air temperature inside the twin greenhouse during the day exceeded 46 degrees. The system lowered it in the experimental greenhouse to 38 degrees. On May 13, the maximum temperatures reached in the two greenhouses 40 and 36, respectively. No significant difference was seen on May 14 due to passing clouds, in addition to interruption in measuring the air temperature inside the experimental greenhouse, as shown in Figure IV-9. On May 18, the maximum temperatures were 37-44, respectively. In the next day, the weather was cloudy, and this explains the temperature fluctuations in Figure IV-10. On the last day, the difference between the maximum temperatures was 31-37, respectively. This means that the cooling system using shading may be the best solution to reduce the temperature inside Greenhouse if the effect is not compared to the cost of the system, which is within the reach of all.

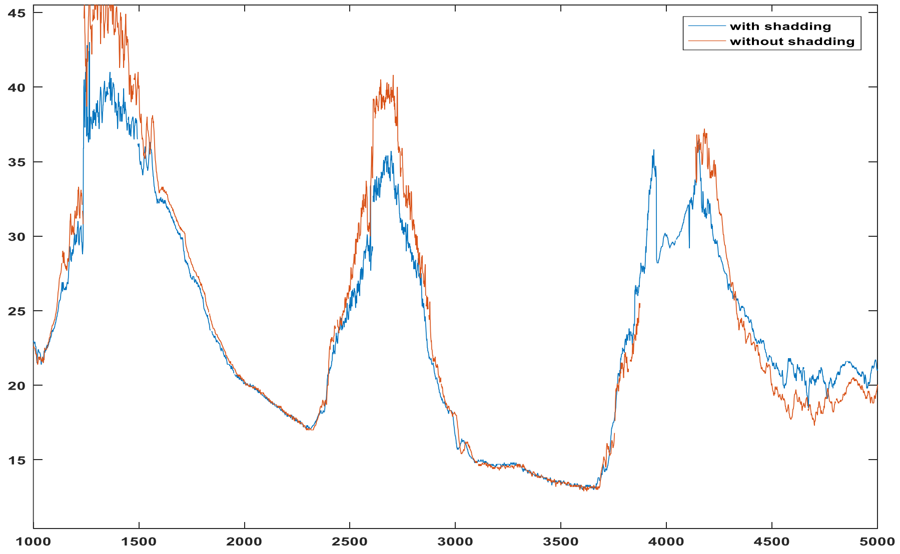


Figure IV-9: The difference in air temperatures entered the experimental and twin greenhouses during the days 12, 13 and 14 May 2023.

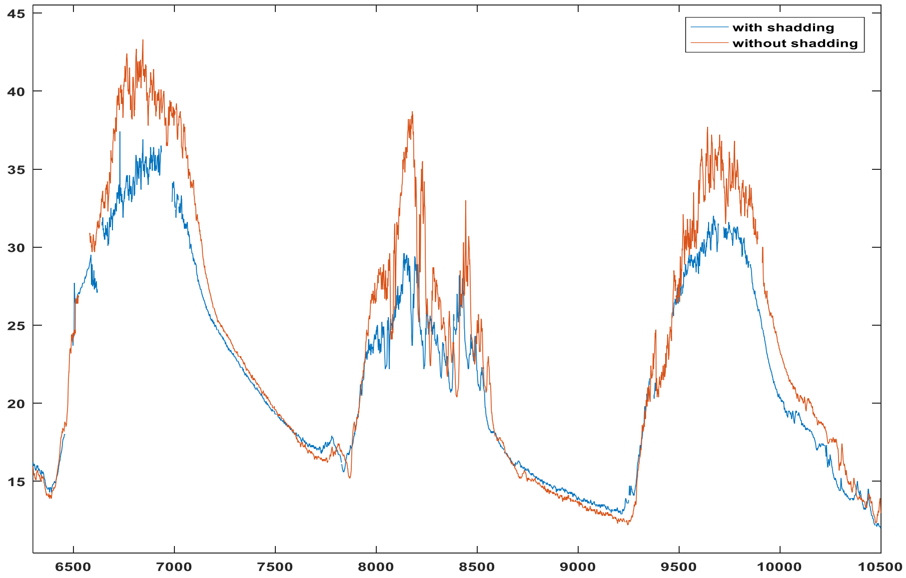


Figure IV-10: The difference in air temperatures entered the experimental and twin greenhouses during the days 18, 19 and 20 May 2023.

IV.4 Fan pad system

The trials were conducted from June 4 to June 15, 2023, at the same site mentioned in the previous trials. for the purpose of cooling the greenhouse. We installed an economical evaporative system (pad and chopper) with a water recovery and reuse system so that we preserve water and rational use of it so that during the evaporation of water we waste only 100 ml per minute. Based on standard engineering data, it is recommended that the temperature inside the greenhouse be kept below 30-32°C [68].

The Figure IV-11 presented in the graph depicts a comparison between the ambient temperatures and the temperatures inside the twin greenhouse over the period from June 4th to June 15th. It is evident that there is a significant increase in temperatures within the twin greenhouse, with peak temperatures ranging from 18°C to 50°C during the peak hours of 13:00 to 14:00. This rise in temperatures can be attributed to the impact of global warming within the greenhouse.

Similarly, when comparing the temperatures inside the experimental greenhouse to the ambient temperatures, a notable difference can be observed during the daytime, exceeding 10°C. Particularly, during the hot and dry weather from days 8 to 10, where temperatures ranged from 25°C to 50°C, the difference reached up to 4°C during the day. This variance can be attributed to the effectiveness of the large evaporative system employed in the greenhouse, despite its economical cost not exceeding 7000.00 DZ (currency).

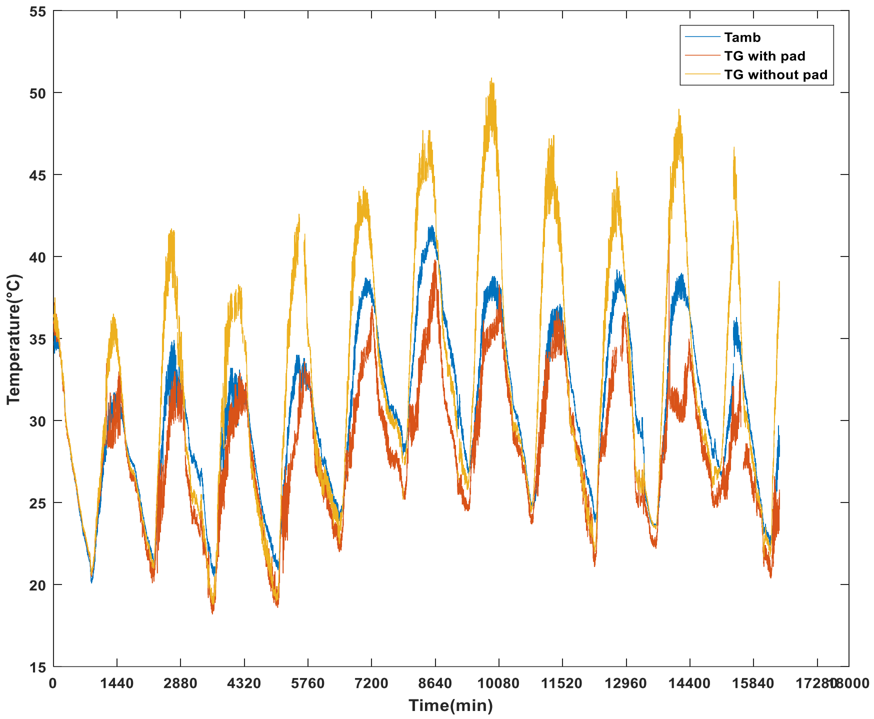


Figure IV-11: The difference in air temperatures entered the experimental and twin greenhouses and ambient temperature during the days (4-15june).

To ensure optimal water utilization, a water recovery system was implemented to replenish moisture in the pad. To assess the quantity of water lost and evaporated within the experimental greenhouse, we established a controlled water flow rate. The downward flow from the water tank was set at 6 L/min, while the upward flow was maintained at 5.9 L/min. This configuration allowed for an evaporation rate of 100 mL/min. The observed evaporation rate demonstrates an economically viable and rational performance in comparison to the evaporation system.

The graph shows the temporal variation of temperature and humidity in the double greenhouse, as shown in Figure IV-12. Over the course of the three days of the experiment, we observed a significant inverse relationship between temperature and humidity. As the temperature rises, the humidity decreases, and vice versa. These results confirm previous studies and reaffirm the well-established inverse relationship between temperature and humidity.

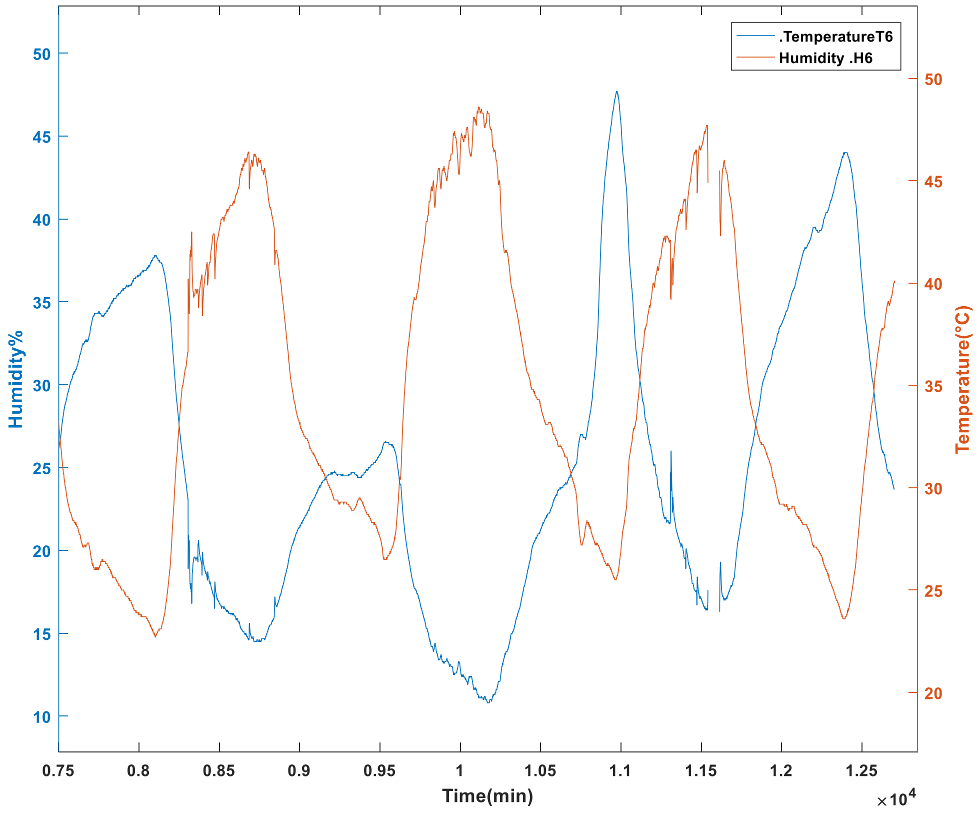


Figure IV-12: Changes of temperature and humidity in the twin greenhouse in terms of time.

The experimental values of Tow, Tdo, and Tdi were accurately measured and recorded as 24.9 °C, 27.63 °C, and 25.5 °C, respectively. These temperature measurements played an important role in evaluating the average cooling capacity of the pad wall within the experimental setup.

To evaluate the effectiveness of the cooling system, the efficiency of the cooling system was calculated and monitored throughout the duration of the experiment. The obtained value for the efficiency of the cooling system was determined to be 0.67, indicating that approximately 67% of the heat generated within the system was successfully dissipated.

Further analysis was carried out to verify the dynamic behavior of the cooling system efficiency. Figure IV-13 (a) and (b) present the changes in efficiency during the daytime period on the 9th and the nighttime period on the 10th of June 2023. Notably, the efficiency of the cooling pads peaked at 95% during the daytime period, with maximum efficiency occurring around 14:00. This indicates that the cooling system was very effective in maintaining a suitable temperature during extreme heat conditions during the day.

In contrast, at night, the efficiency of the cooling system is observed to be lower, not exceeding 40%. This indicates that the cooling system has reduced effectiveness during relatively cold periods, indicating its sensitivity to ambient temperature changes.

These results demonstrate the importance of the cooling system in managing and regulating temperatures within the experimental environment. Notable differences in efficiency emphasize the system's ability to adapt to different climatic conditions, with improved performance in high-temperature scenarios and slightly decreased efficiency during mild conditions. These insights contribute to an understanding of the cooling system's capabilities and help improve its design and operation to improve greenhouse climate control.

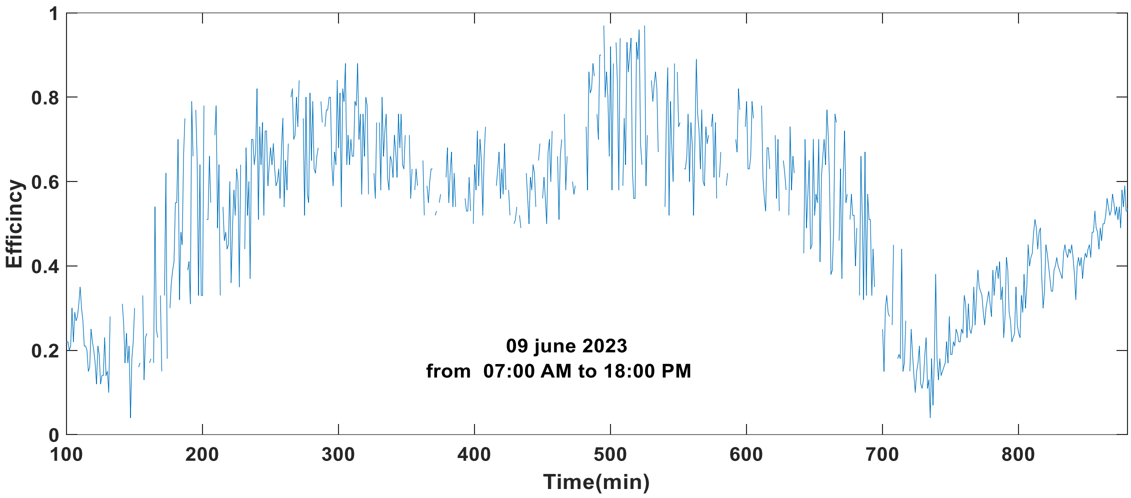


Figure IV-13 (a): Changes in the evaporative system efficiency values at daytime

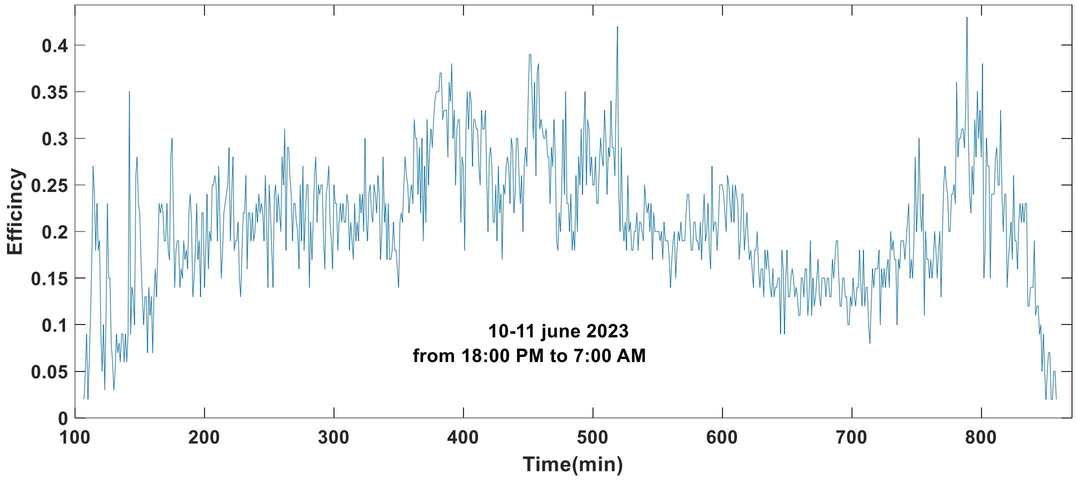


Figure IV-13 (b): Changes in the evaporative system efficiency values at nighttime.

The figure IV-14 was used to analyze and compare the air temperature fluctuations within two experimental greenhouses, a double greenhouse, and the ambient ambient temperature. The aim was to evaluate the effectiveness of the greenhouse design and the pad effect, which represents the air temperature near the pad.

The scale (TG plate) showed remarkable consistency in the range of temperatures, maintaining values between 17 and 25 °C. This is noteworthy considering the high ambient temperatures, which reached 40°C. The ability of a pillow to regulate air temperature within such a narrow range indicates its effectiveness in providing stable, suitable conditions for plants.

By contrast, the experimental greenhouse, with the gauge (TG with pad) placed in its center, displays an observable temperature gradient. As one moved away from the pad, the temperatures gradually increased. However, even at the farthest distance from the pad, temperatures never exceeded 35°C. This indicates that the design of the greenhouse, in combination with the strategic placement of the pad, effectively distributes and moderates the temperature within the structure.

Conversely, the double greenhouse experienced much higher temperatures, up to 50°C. This large difference can be attributed to the greenhouse effect, whereby solar radiation is trapped and amplified within the enclosed space. The absence of an evaporative system and a shading system contributed to this large temperature variation.

These results highlight the importance of the strategic placement of temperature-regulating elements, such as pads, in maintaining optimal growth conditions. The observed temperature changes within the different greenhouses emphasize the importance of effective heat management and underscore the need for careful consideration of environmental factors in greenhouse cultivation systems.

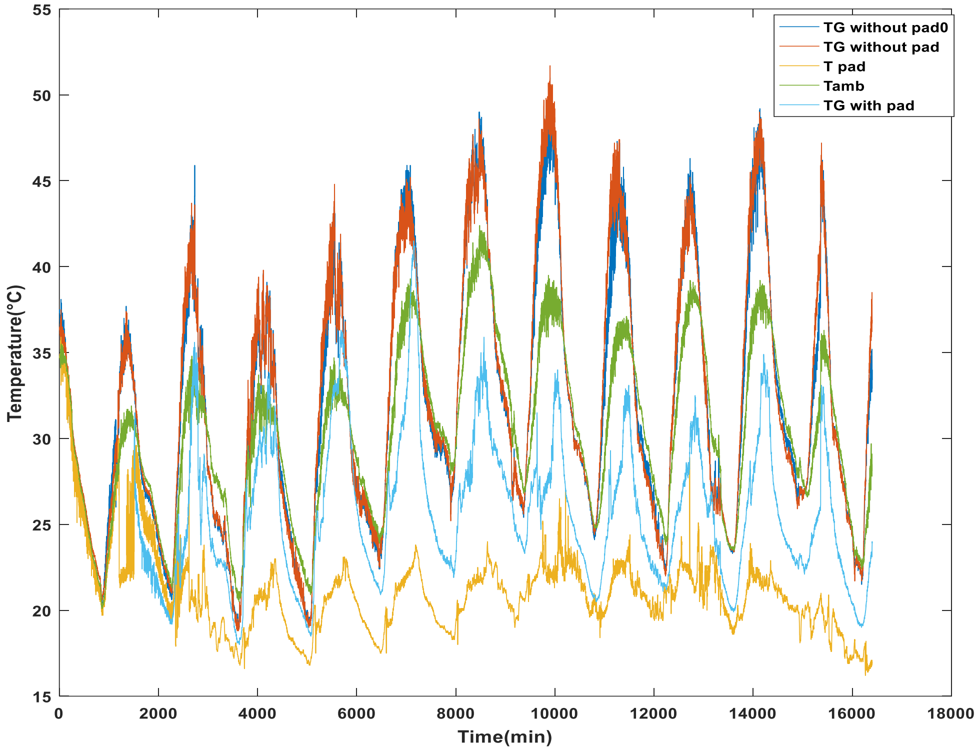


Figure IV-14: The difference in air temperatures entered the experimental and twin greenhouses and temperature near the pad and ambient temperature during the days (4-15june).

IV.5 Conclusion

The completion of this last chapter marks the culmination of our research journey, in which we present the results and engage in discussions about experiments conducted in experimental and control greenhouses. While striving for meaningful results, we encountered many challenges throughout the process, with unforeseen weather conditions, sandstorms, and rainfall disrupting our measurements. In addition, the scarcity of resources, time constraints, and the inherent difficulty in carrying out real-life experiments present additional obstacles. It is worth noting that these experiments usually require several years to complete, but we succeeded in shortening the timeline to only four months, yet we still achieved similar results to other international studies. The heating system achieved good results. As for the cooling systems, the evaporative system was more efficient. When integrating the shading system, efficiency increases.

Despite these challenges, we have succeeded in obtaining valuable results from our research. Adverse weather conditions, as unpleasant as they were, provided us with an opportunity to assess the resilience and effectiveness of heating and cooling systems under extreme conditions. The variation in temperature, caused by fluctuating weather patterns, enabled us to measure the adaptability of the systems and their ability to maintain optimal conditions within the greenhouse.

Limited resources and time constraints prompted us to improve our experimental design and data collection methods. Through the use of careful planning and careful execution, we have been able to maximize the utilization of available resources and produce reliable results. Moreover, the accuracy and efficiency of our research process has allowed us to achieve results that are in line with international standards and contribute to the current body of knowledge in the field of greenhouse technology.

Although our research journey has been arduous, the challenges we faced have served as valuable lessons and opportunities for growth. The ability to overcome these obstacles is a testament to the dedication and perseverance of the research team. The results obtained from this study have the potential to drive advances in greenhouse technology, particularly in regions with similar weather conditions and limited resources. By showing similar results to international studies, we highlight the relevance and applicability of our findings on a global scale.

General Conclusion

General Conclusion:

In conclusion, this Master's thesis presents the results of an experimental study conducted on a double-span greenhouse prototype at a 1/10 scale, focusing on the "Implementation of HVAC systems to manage the greenhouse climate." The greenhouse had various systems to manage the greenhouse microclimate, including heating and cooling systems. The prototype was designed and installed at the experimental platform of the Applied Research Unit in Renewable Energies (URAER) in Ghardaïa.

The observed results in the prototype are highly encouraging, demonstrating the effectiveness of the implemented cooling and heating systems in maintaining stable temperatures throughout the year. These findings highlight the suitability of the proposed techniques for creating comfortable and acceptable microclimates in extreme ambient conditions.

In the first section of the study, a novel solar latent thermal energy storage (LTES) system was developed, designed, and fabricated to provide heating for the greenhouse during winter. The LTES system exhibited high performance, effectively maintaining the desired temperature levels.

The second section of the study focused on examining two cooling systems for the greenhouse. The first system involved the implementation of a shading mechanism, which successfully managed the internal temperature of the greenhouse, preventing excessive heat gain. The second cooling system utilized a FAN-PAD system that incorporated palm fiber materials. This system demonstrated remarkable efficiency in effectively managing the greenhouse's internal climate.

Based on these notable results, the implemented HVAC systems in this study offer an effective alternative to conventional air conditioning systems, particularly in regions characterized by hot and arid climates. These systems demonstrate lower operating costs and provide sustainable and energy-efficient solutions for greenhouse climate management.

In terms of future perspectives, further research and development efforts should be undertaken to optimize and refine the implemented HVAC systems. This includes integrating sustainable energy sources, employing high-quality sensors for precise climate control, and continuously improving the HVAC system design. Additionally, conducting long-term studies and real-world implementations would provide valuable insights into the long-term performance and practicality of the proposed systems.

Overall, this Master's thesis contributes to advancing greenhouse climate management, providing valuable findings and recommendations for developing efficient and sustainable HVAC systems in agricultural practices, thereby promoting a more sustainable and resilient future for greenhouse farming.

However, there are several promising avenues for future research and development:

- Advanced control systems utilizing AI and machine learning algorithms can optimize system performance, improving energy efficiency and precise climate control.
- Further optimization of shading systems and alternative cooling techniques should be pursued to enhance temperature management.
- Water management strategies, crop-specific climate control, economic analysis, long-term performance studies, simulation modeling, and collaboration among stakeholders offer promising opportunities for advancement in this field.

By addressing these future perspectives, researchers can continue to improve the efficiency, effectiveness, and sustainability of HVAC systems in managing the greenhouse climate. This will contribute to advancing agricultural practices, ensuring food security, and promoting sustainable practices in the face of changing environmental conditions.

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